Dynamic Network-Wide Traffic Signal Optimization

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Abstract

Nowadays, many cities in the world are suffering from problems like congestion, pollution, and traffic accidents which are caused by vehicular traffic. The correct scheduling of traffic lights can help to alleviate these problems by improving the flow of vehicles through the cities. The main aim of this dissertation is to build an approach to find the good traffic signal plans for a large area.

The two major features of the approach developed in this thesis are real-time and system-wide. Since traffic flow changes with the time of day, the real-time computation of the traffic signal plans can improve the operation efficiency of traffic lights compared with fixed signal plans which is an old but still often used technology in the world.

The proposed approach is the serial optimization with a hierarchical control framework. The upper level is the level for macro control strategies including a network partition strategy and a network signal coordination strategy. The network partition strategy means that the urban network is partitioned into smaller sub networks based on the network's topological graph and intersections' priority order. The priority order is computed by the sorting model of priority order (SMoPO), which offers the opportunity for the higher priority intersection to be coordinated earlier and to obtain more benefit. The network signal coordination strategy is developed to determine which intersections form a coordination pair and which traffic streams need to be coordinated. This strategy converts the optimization problem into a much simpler one. The number of operations and the computation time to solve this optimization problem drops largely. The lower level is the level for micro parameters calculation, in which a method for the computation of the optimal relative offsets is proposed which is based on cyclic flow profiles.

All of the developed strategies were programed and interfaced with the microscopic simulation tool “SUMO”. To verify the success and the dynamic feasibility of strategies, the computation speed tests were done in three-by-three to sixty-by-sixty grid nets to demonstrate the real-time feasibility of the approach.

After that, microsimulation studies have been performed to evaluate the performance of the strategies. The first case study was a hypothetic eight-by-eight grid net with varied traffic demands and link lengths, and the results revealed that the strategy was effective when the intersections were not oversaturated. The others were two real networks in Braunschweig City, whose input data was from the Project AIM (Application platform Intelligent Mobility). The simulation results showed the delay time was decreased on average in both cases compared to Webster’s model.

Keywords

Adaptive Traffic Control, Network Partition, Real-Time Traffic Signal Optimization, Priority Order, Offsets Optimization.

Zusammenfassung

Der motorisierte Individualverkehr führt in fast allen großen Städten der Welt zu Staus, Umweltverschmutzung und Unfällen. Eine gute Anpassung der Steuerprogramme von Lichtsignalanlagen (LSA) an die jeweilige Verkehrssituation kann dazu beitragen, den Verkehrsablauf flüssiger, weniger umweltbelastend und sicherer zu gestalten. Das Hauptziel dieser Arbeit ist die Entwicklung eines Verfahrens, welches diese Anpassung auch für große Städte mit einer Vielzahl von LSAs ermöglicht.

Diese Arbeit folgt dabei zwei Zielvorgaben. Das zu entwickelnde System soll realzeitfähig sein und auch große Städte mit einigen tausend LSA versorgen können. Die Realzeitkomponente ist von Bedeutung, weil die verkehrliche Nachfrage sehr starken und teilweise nicht vorhersehbaren Schwankungen unterliegt. Von einem solchen adaptiven Verfahren kann erwartet werden, dass es effizienter ist als die Festzeitsteuerungen, die noch immer in vielen Teilen der Welt benutzt werden.

In dieser Arbeit wurde zu diesem Zweck ein serielles Optimierungsverfahren entwickelt, das in ein hierarchisches Steuerungsrahmenwerk eingebunden ist. Die übergeordnete Ebene enthält ein Verfahren, mit dessen Hilfe ein Netzwerk in Teilnetze zerlegt werden kann. Dieses Verfahren basiert auf dem topologischen Graphen des Netzwerkes und der Prioritätenfolge der Kreuzungen des Netzwerks. Die Prioritätenfolge wird durch das in dieser Arbeit entwickelte Verfahren Sorting Model of Priority Order (SMoPO) berechnet, mit dessen Hilfe festgelegt wird, wann im Laufe des Optimierungsprozesses welche Kreuzung optimiert wird – Kreuzungen mit einer höheren Priorität zuerst, die weniger wichtigen später. Darüber hinaus

wurde für diese Ebene ein Koordinierungsverfahren entwickelt, mit dem bestimmt werden kann, welche Paare von Kreuzungen jeweils zu koordinieren sind. Dieser Ansatz reduziert die Komplexität dieses Optimierungsproblems dramatisch, weil es eine Unterteilung eines großen Problems in viele kleinere ermöglicht. Die untere Ebene dieses Rahmenwerkes ist die Berechnung der Mikroparameter der einzelnen Kreuzung. Die optimalen Offsets werden mit Hilfe einer Methode berechnet, die auf zyklischen Flussprofilen basiert.

Alle in der Arbeit entwickelten Verfahren wurden in Computerprogrammen umgesetzt und mit einer Schnittstelle zu dem mikroskopischen Verkehrssimulationstool „SUMO“ versehen. Um die Realzeitfähigkeit der Strategien zu überprüfen, wurden Geschwindigkeitstests für Drei-mal-Drei bis Sechzig-mal-Sechzig Quadratgitternetze durchgeführt.

Anschließend wurden mehrere Fallstudien mit SUMO durchgeführt, um die Qualität des neuen Verfahrens zu evaluieren. Die erste Fallstudie war ein künstliches Acht-mal-Acht Quadratgitternetz mit variierender Verkehrsnachfrage und Kantenlängen. Die Ergebnisse haben gezeigt, dass die Strategie effektiv ist, wenn die Kreuzungen nicht übersättigt sind. Die anderen Fallbeispiele waren zwei echte Netze aus dem Braunschweiger Stadtgebiet mit Inputdaten aus dem Projekt AIM (Anwendungsplattform Intelligente Mobilität). Auch hier konnte die neue Strategie die Verlustzeiten in beiden Fällen im Vergleich zum Webster-Modell verringern.

Keywords

verkehrsabhängige LSA-Steuerung, Netzwerkpartitionierung, echtzeitfähige LSA-Optimierung, Prioritätenreihenfolge, Versatzzeitoptimierung.

Contents

Chapter 1 Introduction

The traffic light is a crucial tool for urban traffic management. On 10 December 1868, the first traffic light was installed outside the British Houses of Parliament in London to control the traffic in Bridge Street, Great George Street and Parliament Street (University of London, 2013). The gas lantern was turned with a lever at its base so that the appropriate light could face the traffic. The first electric traffic light was developed in 1912 by Lester Wire, an American policeman of Salt Lake City, Utah, who also used red-green lights (Mary Bellis, 1952). Since the 1950s, the optimization for traffic signal timing has been researched. Later, some traffic signals had been regarded as the system or the net, so the system-wide or network-wide traffic signal optimization appeared. The system-wide (or network-wide) control is the method for real-time adjustment (or demand-responsive) of the signal timings of all traffic lights in a road network to achieve the reduction in overall congestion which is consistent with the chosen system-wide measure of effectiveness (MOE) (James and Daniel, 1997).

1.1 Motivation

Nowadays, lots of cities in the world suffer from an excessive vehicular traffic that provokes severe problems like pollution, congestion, safety, parking, and many others. Since changes in the urban area infrastructure are usually difficult and costly, a correct scheduling of traffic lights can help to alleviate these problems by improving the flow of vehicles through the cities.

Furthermore, there have been ample practical proofs that traffic conditions can be improved by optimizing the traffic signal settings. Taking SCOOT (Split Cycle Offset Optimization Technique) (Hunt, et al. 1981; Robertson and Bretherton, 1991) and SCATS (Sydney Coordinated Adaptive Traffic System) (Sims, 1978; Sims and Dobinson 1979; Luk et al., 1982) as examples, which are traffic adaptive control system, they have been operated successfully in cities such as Beijing, London, Sao Paolo and Southampton etc. The results of implementation surveys of SCOOT reported that the typical reductions are 8% of travel time, 22% of delay and 17% of stops. The evaluation results of SCATS suggested that the savings are average 7.8% of travel time, up to 28% of delay and up to 42% of stops (Dey et al., 2002).

The adaptive traffic control systems were rarely used, although they gain in effectiveness. For instance, in The USA, less than 1% traffic lights are controlled by the adaptive control system (Fehon, 2004). Why isn't adaptive control more pervasive? There are both subjective and objective reasons (Hadi, 2002). The subjective reasons could be:

1) Agency's willingness to deploy an adaptive control system.
2) Concern about the adaptive signal control system can not perform as well as the plans selected by traffic engineers.
3) Unconvinced that the system suits their city too, feel likely to be effective for arterial roads but not for grid networks.
4) Lack of understanding of adaptive control system concept. For example, people believe the system can not do a good job because it does not provide the green wave for everyone.
5) Concern that difficulties might arise during the implementation and operation of a system. For instance, some agency said the staff will not be able to keep up with the workload, it is too complicated.
6) Concern about using a foreign system.

The main objective reasons contain:

1) The initial and maintenance of the adaptive control system is often too costly. Besides, if there is a system already, can't afford to discard it. Ghaman's report noted that 70% of agencies think it is too costly (Ghaman et al., 2004).

2) The system has rigorous requirements for detection. Moreover, the detector loops have the relatively high rate of failure, which would tend to reduce the reliability and effectiveness of the adaptive systems.
3) Be shortage of personnel with the required expertise.

However, the development of detection patterns like video detectors, blue tooth detectors, GPS etc., as well as, the development of information technology in the last 20 years offers the opportunity to realize the adaptive control. The Traffic Signal Timing Manual reported that, “The use of 20-year-old technology and infrastructure may satisfy the requirement for the signal to display green, yellow, and red, but it may not offer the opportunity to efficiently operate the system or provide preferential treatment for a certain type of user to meet the policies and desires of the community.” (Peter Koonce et al., 2008).

In terms of the immediate financial cost, the financial benefits, such as the saving of time spent in congestion, fuel consumption, air pollution, safety, and workload outside, may shift the attitude. It is common that many agencies have not updated the traffic signals for five years. However, the traffic volume may have changed. So the cost from detectors is needed, even for the update of the fixed-time control.

At present, many practical optimized pre-timed systems are operated in a time of day (TOD) mode. A day is segmented into a number of time intervals, and a signal timing plan is predetermined for each time interval. Typically three to five plans are run in a given day. The basic premise is that the traffic pattern within each interval is relatively consistent, and the predetermined timing plan is best suited for the condition of this particular time of day. The predetermined timing plan is often obtained with the inputs of design flows by applying the Webster’s formula (Webster F. V., 1958), or using the optimization tools, such as TRANSYT (Robertson D.I., 1969). However, the real-world traffic demands are intrinsically fluctuating and the traffic flows at intersections may vary significantly even at the same time of day. Therefore, monitoring the traffic flow via vehicle detectors is the prerequisite of any optimization strategy.

The traffic actuated signal control is another way to optimize signals, which reacts dynamically to the traffic flow to improve the performance of the intersection. Even if the actuated traffic control improves the traffic conditions at a single junction, it might not result in benefits to the system as a whole (Dominik Grether, 2013). Because the actuated traffic control may lead the traffic flow to be unstable, traffic actuated signals can perform worse than a fixed-time control in some situations (S. Lämmer and D. Helbing, 2008, 2010). However, in some literature, it was proved to perform better than the fixed time control (Oertel Robert and Peter Wagner, 2011).

As the number of traffic lights installed in cities grows, their joint scheduling becomes complex due to the huge number of the combination. For instance, there are about 2100 traffic lights in Berlin (Elke Breitenbach, 2014). If every traffic light has four phases, every traffic light has at least five parameters need to be optimized, which are four green time lengths and one offset. In other words, the joint scheduling of the traffic lights has at least 10500 parameters. If the cycle time is 60s, the feasible set of the offset is [0, 59]. The best solution of the offsets should be selected from about 60^{2100} feasible solutions. Hence, the use of automatic systems for the optimal control of traffic lights is a necessary choice. What's more, the study of using intelligent techniques for large and heterogeneous cases is still an open issue.

1.2 Objective

In recent years, traffic simulation has been promoted to become one of most used approaches to the analysis of traffic systems. The ability of traffic simulation to emulate the time variability of traffic phenomena makes it a unique tool for capturing the complexity of traffic systems.

The traffic simulation can be classified into macroscopic, mesoscopic, and microscopic. The macroscopic models (Buisson C., Strada, 1996; Elloumi N., 1994) are often based on hydrodynamic flow theories to model traffic as a continuous flow. The mesoscopic models (Moshe Ben-akiva et al., 2002; Jayakrishnan R. et al., 1994) are formulated by speed-density relationships and queuing theory approaches to model individual vehicles at an aggregate level. The microscopic models (Ben-Akiva M., et al., 1997; Fellendorf M., 1996) capture the much more detailed behavior of vehicles or drivers.

The microscopic models are appropriate to evaluate the performance of control strategies at the operational level. There are some commercial simulation tools, such as VISSIM (PTV AG, 2008), Aimsun (J. Barceló et al., 2005), SimTraffic (David Husch, John Albeck, 2006) and others. However, because of the commercial nature or some other reasons, the interface set between the signal optimization strategy and simulation tools is sometimes difficult to work with; the sensitivity analysis is the quite hard work as well. Some open-source simulation tools remedy these defects, such as Simulation of Urban MObility (SUMO, German Aerospace Center DLR), etc.

Due to the nature of microscopic models, the preparation of input data would be very time-consuming and tedious. Also, the micro models are highly sensitive to the errors or variation in input demand data, their calibration is not trivial. Therefore, the microscopic models are usually applied to the small networks (W. Burghout and J. Wahlstedt, 2007). The mesoscopic models usually have fewer parameters to calibrate, and are less sensitive to errors in network coding or demand variations. Therefore, it is more suitable for optimizing the signal control of the extensive network.

The one aim of the research is to develop a network-wide traffic signal optimization strategy by analyzing and employing the characteristics of traffic flow on the road. The optimization strategy to be developed has the following objectives in mind:

1) The optimization strategies can response to the monitored traffic status automatically.
2) It can be used in any road network since it is a general control strategy that does not aim only to some specialized networks like arterials or grid ones.
3) The strategy can be applied to a huge network, like a whole city.
4) The efficiency of the optimization should not scarify the safety of road users.

The other aim of the research in this thesis is to develop the application of traffic flow theory further and the methods of signal coordination.

The approach to be developed here is the serial optimization with a hierarchical control framework. The strategy can be attributed to two levels. The upper level is the level for the macro control strategies, in which the signal optimization for a certain amount of intersections is broken down to the signal optimization of adjacent intersections in some certain sequence. At this level, which intersections are coordination pairs and which traffic streams should be coordinated will be determined. Generally, in the traffic adaptive control systems or optimization tools, the coordinated links and coordinated phases are often predetermined. However, in this control strategy, they are determined by the real-time traffic status. The lower level is the level for the micro parameters calculation, in which the optimal signal timing plan of each intersection is worked out. At the upper level, some mathematical models are built, and some control strategies are designed. At the lower level, some parameter estimation methods are proposed.

From the viewpoint of the optimization process, the control strategy proceeds in the following steps. First of all, all intersections in the network are sorted so that they will be optimized in a fixed sequence. The higher an intersection is ranked, the earlier it will be optimized and the more benefit it will obtain. In this part, a sorting model of priority order was developed. Secondly, the complex urban network is partitioned into smaller, manageable subnets based on the intersections' priority order which has been worked out in the preceding step. This work is finished by the greedy search algorithm combining with the network's topological graph. Thirdly, the pairs of coordinated intersections and coordinated links in the subnets are determined by the subnet coordination strategy. This step is based on the similar principle of the network partition strategy because the network partition and the signal coordination should be integrated with the uniform objective. After the subnet inside optimization, some adjacent subnets that are suited for coordinating each other could be found by the proposed strategy, for instance, they have a closed common cycle time. Then the boundary intersections of the adjacent subnets are coordinated. At last, the optimized timing plans of each intersection are estimated.

1.3 Thesis overview

This work is organized into eight chapters as follows.

Chapter 2 introduces the literature on traffic signal optimization, the control systems, and computer optimization tools. The research on signal optimization that has been performed can be classified into two categories. The first one supposed that signal optimization cannot affect the route choices of drivers. The other assumed the contrary, i.e. that signal optimization does affect the route choices of drivers. The one method to the problem of signal optimization without affecting the route choice is heuristic algorithms. The other method is to work out the optimal traffic signals by establishing some principles. The related research in each category will be reviewed in this chapter in chronological they appeared respectively. Most of the better-known control systems will be introduced, such as SCOOT, SCATS, RHODES, OPAT, etc. The existing commercial computer optimization tools, TRANSYT, Synchro, PASSER, and TSIS-CORSIM will be introduced too, and the comparisons among the first three tools will be done.

Chapter 3 discusses the intersections' priority order, which is the list of orders that all intersections will be optimized in the sequence. A method to resolve the optimal priority order named as Sorting Model of Priority Order (SMoPO) will be built. It can work out the optimal priority order according to the real-time traffic state of the network. Also, the critical intersection will be determined by this method, which is simply the first one in the order list. Secondly, the algorithm for working out the model will be introduced. Finally, two cases will be presented. The work of sorting priority order is the base of the following network partition strategy and network optimization strategy.

Chapter 4 is dedicated to solve the problem whether or not the network needs to be partitioned into some small subnets and how to partition. First of all, the present partition methods will be reviewed. Secondly, the working principle and algorithm of the proposed partition strategy will be described. Finally, a case will be employed to explain further the working mechanism of the proposed partition strategy.

Chapter 5 introduces the traffic signal coordination strategy for the intersections inside the subnets and the boundary intersections between adjacent subnets. The working principle and algorithm of the strategy will be introduced at first, and then it will be explained by a case. At this point, the macro control strategy for system-wide signal optimization is stated completely.

In Chapter 6, the micro-parameter estimation of the optimal timing plans of each intersection is discussed. The green splits are directly adjusted by the rule that it is in proportion to the corresponding ratios of flow to saturation flow. To determine the optimal relative offsets, firstly, some existing computation methods will be reviewed. Secondly the proposed method that makes use of the cyclic flow profile and cyclic delay profile on the coordinated links will be described. Finally, the performance of the methods will be quantitatively shown by simulation tests.

In Chapter 7, the experiments are designed how this network-wide optimization strategy can be simulated in SUMO (an open source simulation tool). The first part will be amounts of speed tests of the proposed models and strategies in different size of the network. The fast computation speed is the premise of real-time execution of the proposed optimization method. The first study case is a grid network with 64 intersections with varied traffic demands. The second one is the real network of Braunschweig city which contains two scenarios.

To conclude the thesis, Chapter 8 summarizes the main contributions and disadvantages of the approach, and outlooks promising directions for future work.

Chapter 2
Review of research on traffic signal optimization

The research on traffic signal optimization has been performed since the early 1960s. In 1967, there have been three functioning digital-computers installations for traffic control, one in Toronto, Canada, one in San Jose, California, and one in Wichita Falls, Texas (Denos C. Gazis, 1967). This topic is still under investigation today, by putting together new powerful and modern optimization algorithms and innovative methods to the massive amount of traffic data, even for the whole systems.

The research on traffic signal timing optimization that has been performed can be classified into two categories. The fundamental difference is whether the signal timing optimization affects the route choice or not.

- Category 1: The route choices are <u>independent</u> of signal timing optimization.

When optimizing signal timings, many well-developed heuristic algorithms have been used, such as Genetic Algorithm, Hill Climbing Algorithm, Shotgun Algorithm, Simulated Annealing Algorithm, Ant Colony Algorithm etc. These heuristic algorithms search for the optimal solution within acceptable computation cost, but without the guarantee of optimality. The advantages of these algorithms are that they are simple and practical, and easy to be accepted by users. The foundation of these methods in signal timing optimization is the accuracy of the fitness function, such as the Performance

Index (PI) or Measures of Effectiveness (MOEs) of the control system. The search directions of the heuristic algorithms are determined by comparing PI of alternative solutions. If the fitness function cannot reflect the practice or has large noise, then the optimal solution by heuristic algorithms may be a false one although the heuristic algorithm have been known to be feasible and smart. Some researchers considered this problem too and proposed methods to solve the noise problem, such as cross entropy methods. To sum up, there have been some well-developed heuristic algorithms and applied in the problem of traffic signal timing optimization, but the practical effect of the optimal solutions by them still need to be discussed.

- Category 2: The route choices are dependent on signal timing optimization.

Some researchers assumed the signal coordination would change the route costs according to the Wardrop Equilibrium Theory (John Glen Wardrop, 1952; Yosef Sheffi, 1985). The change of route choices will lead to a change of the traffic flows, which in turn requires an update of the optimal timing plans. This process is shown in Figure 2-1. Therefore, the interaction between the signal optimization and the traffic assignment is formed. Researchers mainly used Iterative Optimization Assignment (IOA) to work out the optimal solution. The IOA procedure continues until it converges, and the solution is called the Mutually Consistent (MC) approach.

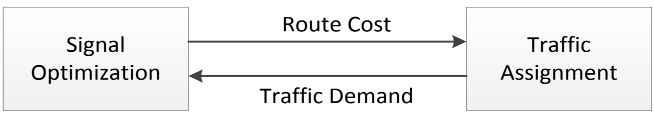


Figure 2-1 Interaction of signal optimization and traffic assignment

The MC approach is logical, but there are three suspicions on its feasibility. Firstly, people's perception of the change of route cost, e.g. the travel time, is not so accurate to initiate a route change. For instance, people may alter the route if the travel time is reduced from 1 hour to 40 minutes. However, the reduction through traffic signal optimization may be not so strong. Therefore, an improvement in a small amount of travel time, like three minutes, may not impact the route choice. In other words, in this situation, signal optimization has no impact on traffic assignment. Besides that, people's perception of travel time is not so real-time that they change their route. Their estimation to travel time of a particular route usually is based on their experience or inquiry to a certain web-based tool or the application in smartphone, so route choice will not fluctuate with the change by traffic signal optimization.

Secondly, if signal optimization is done through detecting the real-time traffic flow, the optimized signal timing plans have been based on the changed routes. For instance, if the signal timing is optimized every 10 minutes according to the traffic demand of previous 10-minutes, this traffic demand is the result of route choice.

Thirdly, the travel time is one of the factors to affect the traffic assignment, not the only factor. In the theory study, people can suppose all other factors that affect the traffic assignment are fixed, and only travel time is changeable. Then the interaction loop in Figure 2-1 is acceptable. However, in practice, the other factors, such as the road condition, the interference of other traffic modes, and the environment, are changing and not predictable. So the effectiveness of this method is suspicious. Moreover, there is no proof for the effectiveness of the Mutually Consistent (MC) approach in field.

2.1 Models and algorithms

2.1.1 Signal optimization is independent of route choices

Category 1 is supposed the route choices cannot be affected by the signal timing optimization.

The heuristic algorithms have been applied to the problem of traffic signal optimization since the 1960s. They are reviewed here in chronological of their application.

- ***Mixed-integer Linear Programming (MILP)***

John D. C. Little (1966) researched the traffic signal synchronization of an arterial by using Mixed-Integer Linear Programming (MILP). The linear program was formulated by problems including: 1) the green bands for two directions must bear a special relation to every signal; 2) upper and lower limits on speed between adjacent signals; 3) limits on change in speed; 4) the split at each signal; 5) upper and lower limits on signal period. The objective was to maximize the sum of the bandwidths for the two directions. The branch-and-bound method was used to solving the mixed-integer linear programs. A 10-signal arterial example and a 7-signal network example were worked out. He has also suggested an extension of his method for synchronizing the lights of city networks. He pointed out that progression design for networks was made complicated by the existence of loops, which made it virtually impossible to keep every driver moving and happy.

- ***Hill Climbing Algorithm (HCA)***

D. I. Robertson (1969) firstly used a hill climbing algorithm to minimize the performance index in TRANSYT. The first step of this algorithm was to calculate the performance index of the network for an initial set of signal timings. The next stage was to alter the offset of one of the signals by a predetermined number of 1/50 cycle units and to recalculate the performance index of the network. If the index was reduced, the offset was altered successively in the same direction by the same number of units until a minimum value of the index was obtained. If the initial step increased the value of the index, the offset of the signal was altered in the opposite direction to that of the initial step until the minimum value was obtained. The offset of each signal in turn was adjusted in this way.

- ***SPSA and Neural Networks***

T. Nakatsuji and T. Kaku (1991) introduced a multilayer neural network to realize a self-organizing traffic control system. The neural model inputs split lengths of signal phases and outputs measures of effectiveness such as queue lengths or performance indices. The operation was separated into two processes, a training process and an optimization process. In the training process, iterations of the training operation by the back propagation method were effective in forming a steady input-output relationship between splits and measures of effectiveness. In the optimization process, a stepwise method combining the Cauchy machine with a feedback method was proposed. The

Cauchy machine is a sort of Monte Carlo method and gives the adjustments in a statistical way. Spall J.C. et al. (1994) introduced the weight estimation in Neural Networks by a form of stochastic approximation. M. James C. Spall and Daniel C. Chin (1997) proposed an approach for optimal signal timing based on a neural network (or another function approximation). It served as the basis for the control law with the weight estimation occurring in closed-loop mode via the Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm. The neural network function uses current information to solve the current (instantaneous) traffic problem on a system-wide basis through an optimal signal timing strategy. Papageorgiou (1995) investigated the application of a feed-forward neural network approach to freeway network control.

- ***Simulated Annealing Algorithm (SAA)***

Terry L. Friesz et al. (1992) proposed the simulated annealing algorithm for the equilibrium network design problem. They demonstrated the ability of this algorithm to determine a globally optimal solution for two different networks. One of these described an actual city in the midwestern United States. M. A. Hadi and C. E. Wallace (1994) introduced a phase sequence optimization capability to TRANSYT-7F using the Cauchy Simulated Annealing Algorithm, which is an optimization technique that makes an analogy between optimization problems and the annealing of physical solids. The simulated annealing algorithm was implemented to optimize cycle length, phase sequences, and offsets simultaneously on the basis of the progression opportunities calculated by TRANSYT-7F. The model has been applied in TRANSYT now.

- ***Genetic Algorithm (GA)***

The first appearance of the GA for traffic signal optimization was in a network with four junctions by Foy et al. (1992). The green timings and common cycle time were the explicit decisional variables, and the offset variables were the implicit decisional variable. In the optimization process, a simple microscopic simulation model was used to evaluate alternative solutions based on minimizing delay.

In the following years, many studies investigated GA applications for optimizing traffic control. Hadi and Wallace (1993) combined GAs with TRANSYT-7F to optimize all four of the signal timing variables (cycle length, offsets, splits, and phase sequences). This hybrid GA selected the progression that considers both through bands and short-term progression opportunities within the system as the performance index. They devised two GA models: 1) each alternative solution within a GA generation represented a phase sequence and a cycle length. Offsets and splits were calculated using the TRANSYT-7F hill-climbing procedure. 2) Included the GA offset optimization in addition to phase sequence and cycle length. Three real networks with two intersections were tested by the hybrid GA. The results suggested that both implementations have the potential for optimizing signal phasing and timing compared with PASSER II solutions.

Abu-Lebdeh and Benekohal (1997) considered the problem of signal control in a dynamic environment. They reported that the technique was not ready for online implementation due to the extensive computational time required by the GA. The first to use GAs to optimize all four signal timing parameters simultaneously were Park et al. (1999). This work was further extended to consider multiple optimization strategies in Park et al. (2001). Yin (2000) applied the GA notion to maximize the network reserve capacity by explicitly taking into account only the green split for an isolated signalized junction. User Equilibrium (UE) assignment was used to obtain equilibrium link flows resulting from the upper-level problem.

The sensitivity of GA optimization parameters was investigated by Kovvali and Messer (2002). Halim and Michael (2005) researched the network under congestion by their method. Halim (2006) combined Genetic algorithm with hill climbing optimization method for area traffic control. Jelka Stevanovic (2008) presented the optimization of four basic signal timing parameters and transit priority by GAs and evaluated in VISSIM. In most of these studies, GA’s have been shown to be better at generating signal timings than other optimization tools.

- ***Non-Linear Program (NLP)***

S. C. Wong (1996) presented the group-based optimization of signal timings for area traffic control. The signal timings were formulated as a set of non-linear mathematical programs by using group-based control variables. The Performance Index was evaluated by TRANSYT. The programs were solved by an integer programming method. Wong (1997) presented a parallel computing and a dynamic load balancing scheme for group-based optimization.

- ***Fuzzy logic***

Qinghui Lin, B. W. Kwan and L. J. Tung (1997) formulated a dynamic model to describe the traffic flow at an intersection. Through simulating optimal traffic flow by the dynamic model, an adaptive traffic controller based on fuzzy logic technology was presented. Anderson J.M. et al. (1998) described the investigation made into the feasibility of optimizing a prototype fuzzy logic signal controller with respect to several criteria simultaneously. The controller's sensitivity to the changes in the membership function parameters was demonstrated, and it was not possible to minimize simultaneously even the limited set of performance measures explored (travel times and emissions). Jan-Dirk Schmöcker, Sonal Ahuja and Michael G.H. Bell (2008) presented an approach to multi-objective signal control using fuzzy logic where the membership functions were optimized according to the Bellman–Zadeh principle of fuzzy decision-making.

- ***Ant Colony Algorithm (ACA)***

Yu Wen and Tiejun Wu (2004) introduced ant algorithm in regional signal coordinated control. The proposed ant algorithm searched for the optimal signal offsets to coordinate the adjacent intersections. Artificial ants decided on a signal setting at each intersection to form the signal scheme of the whole considered area. They used the local heuristic information and the artificial pheromone trails to help ants to construct routes. Jiajia He and Zaien Hou (2012) employed the ant colony algorithm for traffic signal optimization. They compared the performance indexes achieved by the signal optimization with Webster's formula, genetic algorithm, and ant colony algorithm by computational experiments. The numerical results showed that ant colony algorithm was a simple and feasible method for signal timing optimization problems.

- ***Particle Swarm Optimization Algorithm (PSOA)***

Jiayu Zhao et al. (2006) used PSO algorithm to optimize hidden layer and output layer weights. The proposed approach showed a high accuracy of the traffic flow forecast. J. Garcı´a Nieto, E. Alba and A. Carolina Olivera (2012) proposed a Particle swarm optimization algorithm to find cycle programs of traffic lights.

- ***Cross-entropy Method (CEM)***

Mike Maher (2007) introduced the cross-entropy method for noisy optimization of the performance index. Later on, he (Maher, 2008) introduced the cross-entropy method to the problem of the optimization of signal settings on a signalized roundabout. He used the cell transmission model to evaluate the performance of any given set of timings. Ronghui Liu and Mike Maher (2010) discussed that knowing the level of the noise in the PI value was essential when applying the model's results in the evaluation. But currently there was little evidence on this in the literature. They tested the noise from the traffic demand variability, the global network supply variability, and the vehicle variability to explore the nature and sensitivity of random processes represented in the model. The results were presented from a large simulation experiment in three networks of varying sizes and complexity by using a microscopic simulator, DRACULA., Moreover, they used the Monte Carlo method to estimate the level of noise. The experimental results provided useful insights and first evidence based on the noise levels existing in Monte Carlo traffic simulation models. Dong Ngoduy and Mike Maher (2011) proposed the optimization of signals in a network by Cross Entropy Method (CEM). The results obtained from the CEM produced a better performance index compared with those from a Genetic Algorithm (GA) approach to the same problem. Mike Maher, Ronghui Liu and Dong Ngoduy (2011) further showed that to find optimal signal solutions by the CEM can be applied both deterministic and Monte Carlo problems, and to fixed-route and variable-route problems.

- ***Harmony search***

Huseyin Ceylan and Halim Ceylan (2012) proposed the Hybrid Harmony Search and Hill Climbing with TRANSYT (HSHCTRANS) model to solve the Stochastic Equilibrium Network Design (SEQND) problem. In the HSHCTRANS model, the meta-heuristic Harmony Search (HS) algorithm was employed as a global search method while the TRANSYT hill climbing routine was used for fine-tuning.

- ***Other models***

Some studies on the optimal traffic signals are reviewed here.

John T. Morgan and John D. C. Little (1964) proposed a method to synchronize the traffic signals for a maximal bandwidth. The bandwidth means the proportion of the cycle, for which a vehicle unimpeded by other traffic, and traveling at a predetermined speed on each section of the main road without meeting any of the lights at red. A serious disadvantage of this goal was that, the bandwidth was almost always insufficient to deal with the amount of traffic that can pass through the system. Some work has also been done by setting the signals to minimize delay or stops by NEWELL (1964) and J. A. Hillier (1966, 1967).

Nathan H. Gartner et al. (1991) proposed a variable bandwidth progression in which each directional road section can obtain an individually weighted bandwidth (hence, the term multi-band). A mixed integer linear programming was used to perform the optimization. Simulation results indicated that this method can produce considerable gains in performance when compared with traditional progression methods.

Markos Papageorgiou (1995) presented a systematic approach to optimal integrated control of traffic corridors involving signal control, ramp metering, motorway-to-motorway control, VMS control, and route guidance. His approach involved the formulation and solution of a linear optimal control problem based on a store-and-forward network type of modeling.

Tang-Hsien Chang and Guey-Yin Sun (2004) proposed a bang-bang like model for the optimization of the oversaturated signalized network. The method attempted to find an optimal switchover point during the oversaturated period to interchange the timing of the approaches. At first, a maximal green time to the maximal arrival rate and minimal green time to the minimal arrival rate was set. Secondly, at the optimal switch-over point, switched the maximal green time to the minimal arrival approach and the minimal green time to the maximal arrival approach.

Yi Jiang et al. (2006) presented a platoon based traffic signal timing algorithm. In their study, 2.5 s was used as the critical headway for a platoon. Their control algorithm preferred the platoon on the major road. When a green indication was initiated on the major road, it will be retained for at least the specified minimum green time. When a vehicle platoon was detected during this minimum green period, and if the unused portion of the minimum green time is larger than the green time extension, then no green time extension is needed. Otherwise, an amount of green time extension was added from the time of the actuation. If a subsequent actuation occurs within this green time extension, a new value of green time extension is calculated and is added to the green from the time of the actuation. The green time extension is not a constant value, and it must be calculated for each vehicle platoon detected. This process continues until it meets terminating conditions. The purpose of this platoon-based actuated control algorithm is to minimize possible interruptions to the vehicle platoons and thus to reduce traffic delays at intersections. The proposed signal control algorithm was effective in reducing traffic delays at intersections with the low traffic volume on the minor road and relatively high traffic volume on the major road, when compared to the conventional signal control methods calculated by CORSIM under various traffic conditions.

Stefan Lämmer and Dirk Helbing (2008, 2009, 2010, 2012) proposed a self-organization approach to traffic light control. The switching rule minimizes the total waiting time. The principle behind their decentralized self-control concept is the combination of two inferior strategies, a stabilization, and an optimizing rule, which allows for a varying sequence of traffic phases and a spatially coordinated, noncyclical operation. The stabilization rule is to define an ordered priority set Ω containing the arguments *i* of all those traffic flows, which have been selected by the supervisory mechanism and need to be served soon in order to maintain stability. Furthermore, the argument *i* of a crowded link *i* joined the set Ω as soon as more than some critical number of vehicles is waiting to be served. It was removed from the set after the queue was cleared, or after a maximum allowed green time was reached. The prioritization rule was based on the anticipated queue length. The anticipation model allows one to predict future arrivals, and to generalize the strategies to serving platoons without any previous stops, i.e. in a 'green wave' manner.

Tobias Pohlmann (2010) developed a new Adaptive Traffic Control Systems (ATCS) prototype. The prototype employs a centralized concept and uses an optimization interval of 15 minutes. Based on the detector counts of previous time intervals and reference traffic demand patterns, a forecasting module estimates the detector counts of the next interval. The next two modules of the ATCS perform an adjustment of cycle length and phase durations and an optimization of offsets. The cycle-time is computed by implementing classic formulas for the calculation of fixed time signal plans. A macroscopic traffic flow model has been used to evaluate the effects of different offset combinations in terms of total delay. Finally, a signal plan transition rule was built.

Hu Pengfei et al. (2011) built two models to find the optimal coordination control plan for each traffic signal in the urban network. They were arterial coordination model and network coordination. The objective of coordination was the maximum weighted sum of bandwidth in both directions. These new models solved any size of network and various types of signal intersection in urban areas, but the extensive computation time may increase greatly with the size of a traffic network.

Qing He et al. (2012) presented a unified platoon-based formulation called Platoon-based Arterial Multi-modal Signal Control with Online Data (PAMSCOD) to optimize concurrently network traffic signal control for different travel modes. Two modes of traffic composition were considered:

transit buses and passenger vehicles in a decision framework that can easily accommodate pedestrians and bicycles. First, when approaching an intersection, travelers can send a green light request to the traffic controller. The green light request included travelers' travel mode, position, speed and requested traffic signal phase. Single requests are categorized and clustered into platoons by priority level and phase. Finally, a mixed-integer linear program (MILP) was solved online for future optimal signal plans based on the real-time arterial platoon request data and traffic controller status.

Holger Prothmann et al. (2009) presented an organic approach to traffic light control in urban areas that exhibits adaptation and learning capabilities, allowing traffic lights to react autonomously to changing traffic conditions.

L. Adacher (2012) applied the generalized "surrogate problem" methodology that was based on an on-line control scheme. It transformed the problem into a "surrogate" continuous optimization problem, and proceeded to solve the latter using standard gradient-based approaches.

2.1.2 Signal optimization is dependent on route choices

Category 2 supposes that the route choices <u>can</u> be affected by the signal timing optimization. The theory combining the traffic control and the route choice can be used for design and operation of traffic control systems as well as evaluation of traffic management schemes and major road proposals. Considering the simple network shown in Figure 2-2 (Dickson, 1981), the network consists of two O-D pairs, AB and CD, and one signalized junction E under two-phase signal operation.

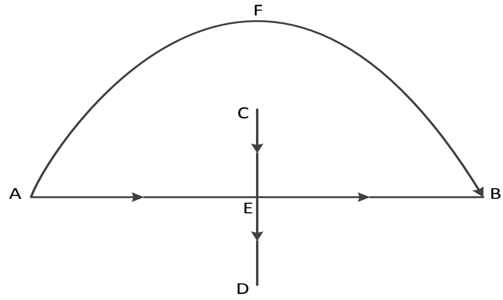


Figure 2-2 Network of Dickson's example

Let λ be the proportion of green time given to the link AEB. To simplify, assume no lost time and hence $1-\lambda$ is the proportion of green time given to link CED. And assume that the travel time on the links is a linear function of flow plus a delay at the intersection plus which is a simple delay formula of the form of $f(q,\lambda)$, plus a critical value T^*. So the travel time and flow relation on the links are:

$$t_1 = q_1 + f(q_1,\lambda) + {T_1}^*,\ (link\ AEB)$$
$$t_2 = q_2 + {T_2}^*, (link\ AFB) \quad (2.1)$$
$$t_3 = q_3 + f(q_3, 1-\lambda) + {T_3}^*, (link\ CED)$$

Let the demand on the network be 1 unit of traffic from A to B and 1 unit from C to D. Only drivers from A to B have a route choice, and let β be the flow on AEB, hence $1-\beta$ is flow on AFB. Namely, $q_1 = \beta, q_2 = 1 - \beta, q_3 = 1$. Thus there are one independent flow parameter β and one signal parameter λ.

Researchers mainly used Iterative Optimization Assignment (IOA) to work out the optimal solution. The entire IOA method could be described as follow:

STEP 0: Initial assignment.
STEP 1: Signal optimization.
STEP 2: Estimate relationship between travel time and traffic flow for each link with signal setting from Step 1.
STEP 3: Reassign traffic with the link performance from Step 2.
STEP 4: Return to Step 1 until convergence criterion is met.

R. E. Allsop (1974) suggested the necessity of combining signal calculation and assignment by pointing out that the routing of traffic in a network was dependent on signal timings according to Wardrop's first principle. He suggested an iterative solution procedure that decomposes the problem into two well-researched sub-problems, i.e. signal optimization and traffic assignment. The signal optimization was performed with the flow patterns from the assignment, and the assignment used link performance functions based upon signal settings from the signal optimization. The suggested method was called the Iterative Optimization Assignment (IOA) procedure in the literature. The IOA procedure continues until it converges, and the solution was called the Mutually Consistent (MC) approach.

Nathan H. Gartner (1975) supported Allsop’s point. It is assumed that all route choices are fixed, resulting in constant flows on each link regardless of the controls imposed on that link and. This assumption would be correct only in the case that the level of service on the controlled link is insensitive to the control settings, which is, of course incorrect. Therefore, it is important to have a model that incorporates both traffic controls and route choice and provides a tool for establishing a system-optimized traffic flow pattern.

Allsop's conceptual algorithm was extended by Allsop and J.A. Charlesworth (1977) and Charlesworth (1977) in which the signal optimization was solved by TRANSYT-7F. The link performance functions were estimated by evaluating travel times for different flow levels with TRANSYT and fitting these points with a polynomial function. This method was called Charlesworth's approach. With various starting points, the procedure was repeated to find other potential mutually consistent solutions. Allsop and Charlesworth carried out an experiment on a small six-junction network.

H. N. Tan et al. (1979) formulated combining control and assignment as

$$\min z(x^*, \lambda) = x^* \cdot t(x^*, \lambda), s.t. x^* \sim UE, \lambda \in F_E, \tag{2.2}$$

and named it the Hybrid Optimization Formulation. Here UE is user equilibrium; F_E is the set of feasible control variables; λ is the green split; x is the flow on path. Two methods were suggested and applied for a simple network. One seeks a local solution via the augmented Lagrangian method which requires path enumerations, and the other seeks a mutually consistent point via the IOA procedure.

For an extensive network, they utilized the fact that flow, which is constrained to be UE, is a function of the control plan, and uniquely determined by the control variables. In other words, the UE problem is convex for the fixed control variables. The new formulation was proposed as:

$$\min z(x^*(\lambda), \lambda) = x^*(\lambda) \cdot t(x^*(\lambda), \lambda), s.t. x^*(\lambda) \sim UE, \lambda \in F_E. \tag{2.3}$$

Abdulaal and LeBlanc (1979) used the same formulation for the network design problem. Only control parameters are considered as decision variables. Sheffi and Powell (1983) also pointed out that $x^*(\lambda)$ may possess non-continuous derivatives with respective to λ at a finite number of points because of a possible change in the number of used paths between some O-D pair by the change of λ. The gradient should be interpreted as a finite difference over the point of derivative discontinuity. Sheffi and Powell, though, argued the derivative can be expected to be piecewise continuous over the regions where a change in λ does not cause a change in the number of used paths between any O-D pair. This potential problem may not occur for stochastic UE problems, where all the paths are always available to a trip maker and the derivative will be continuous for most distributions used in conjunction with stochastic UE models.

M. J. Smith (1979) and Stella Dafermos (1980) developed the formulation. M. S. Al-Malik (1991) and Al-Malik and Gartner (1995) demonstrated that the combining control assignment with Webster's and HCM delay models made SO and UE problems non-convex for intersections with two approaches and two-phase signal operation. Michael J. Maher et al. (2001) combined the problem of trip matrix estimation and traffic signal optimization as a bi-level programming problem with the stochastic user equilibrium assignment. Suh-Wen Chiou (2003) proposed a gradient-based method for area traffic control under equilibrium network flows. Chiou (2008) discussed the problem of finding the maximum possible increase in travel demand and determining optimal link capacity expansions by using the concept of the reserve capacity of signal-controlled junctions. She presented a quasi-Newton method for simultaneously solving the maximum increase in travel demands and minimizing total delays of travelers. Chiou (2010) investigated a non-smooth approach. Lee K. Jones et al. (2013) proposed a robust control for traffic networks named the near-Bayes near-Minimax (NBNM) strategy, which was a compromise between the Bayes and the Minimax solutions. Robust Optimization (RO) was a more recent approach to optimization under uncertainty in which the uncertainty model was not stochastic, but rather deterministic and set-based.

Chungwon Lee and Randy B. Machemehl (2005) recognized the non-convexity of the combined problem and examined the quality of different algorithm solutions with convergence pattern analysis. They investigated the non-convex combined traffic signal control and traffic assignment problem by using four different algorithms and four example networks.

Halim Ceylan and Michael G. H. Bell (2004) solved the design problem of the equilibrium network through a bi-level approach. The upper-level problem is signal setting while the lower level problem is finding the equilibrium link flows based on the stochastic effects of drivers routing. The GA approach is used to optimize globally signal settings at the upper level by calling the TRANSYT traffic model to evaluate the objective function.

2.1.3 Summary of models and algorithms

The main methods in section 2.1 and 2.2 are listed in chronological in Table 2-1. In summary, researchers tried to employ most of the heuristic algorithms in traffic signal optimization problems. The effect of these methods is directly related to the feature of the algorithm. For instance, Hill Climbing algorithm is simple but easy to get local optima while Simulated Annealing Algorithm can avoid some local optima but is more complicated. The most popular algorithm is the Genetic algorithm, and can create better signal plans. Most of the methods' objective is the minimization of Performance Index (PI), and the remainder is the maximization of bandwidth. S.C. Wong's method considered the optimization of the phase sequence that was not optimized in other methods. In a word, the heuristic algorithm is easy to understand and realized, but the practical effect of optimized results largely relies on the accuracy of the objective function or PI model.

Table 2-1 Overview of algorithms for signal timing optimization

Algorithm	First author	Year	Introduction
MILP	John D.C. Little	1966	Synchronization for the arterial. The objective is the maximization of bandwidth.
	Hu Peifeng	2011	
HC	D. I. Robertson	1968	Local optima with the objective of minimization of the performance index. Implemented in TRANSYT.
MC = IOA	Gartner N. H.	1974	According to Wardrop's first principle, route choice, and signal timings should ideally be regarded simultaneously. The Iterative Optimization Assignment (IOA) procedure continues until it converges.
	Allsop R. E.	1977	
	Charlesworth J. A.	1977	
	Chungwon Lee	2005	
SAA	Friesz T. L.	1992	Phase sequence optimization function has been implemented in TRANSYT -7F.
	Hadi M.A.	1994	
SPSA	Nataksuji T.	1991	The operation is separated into two processes, a training process and an optimization process.
	Spall J. C.	1994	
	Papageorgiou M.	1995	
NLP	S. C. Wong	1996, 1997	Area traffic control, constraints of cycle time, green time, clearance time, capacity and offsets.
Fuzzy Logic	Anderson J.	1998	Based on Bellman-Zadeh Principle, find Pareto optima, combined with Genetic Algorithm.
	Niittymaki J. P.	2000	
	Ahuja S.	2006	
	Jan-Dirk Schmöcker	2008	

(continuation of previous page)

GA	Foy M.D.	1992	Implemented in TRANSYT, CORSIM, and PASSER. Show better performance than other algorithms.
	Lee C.	1998	
	Park B.	1999	
	Cree N.D.	1999	
	Yin Y.	2000	
	Rouphail N.M.	2000	
	Halim Ceylan	2004	
	Teklu F.	2007	
	P. Tomich	2007	
	Jelka Stevanovic	2008	
MPO	Tang-Hsien Chang	2004	Optimization for oversaturated network.
ACO	Wen Y.	2004	Artificial ants decide.
	Jiajia He	2012	
GATHIC	Hadi M.A.	1993	Combined Genetic algorithm and Hill Climbing algorithm.
CEM	Maher M. J.	2007 - 2011	Cross-entropy method for noisy optimization of the performance index.
PSO	Zhao J.	2006	Particle Swam Optimization Algorithm for cycle optimization and traffic flow forecast.
	Dušan Teodorovic	2008	
	Kachroudi S	2009	
	J. Garcı´a-Nieto	2012	

2.2 Control systems

An adaptive network control system evaluates and optimizes their control decisions on-line. The traffic flows and signal controls are usually modeled by the system, and allow determining the impact of control decisions on the traffic performance. Using the measures of performance, optimization components search for the best possible signalization for the current traffic demand. This section discusses the selected adaptive network control systems. Besides the systems discussed here, several other adaptive network control systems have been developed and used throughout the world. More extensive overviews and reviews are available in the literature of M. Papageorgiou (2003) and A. Stevanovic (2009).

2.2.1 SCOOT

The Transport and Road Research Laboratory (TRRL) in Great Britain developed The Split, Cycle, and Offset Optimization Technique (SCOOT) in 1973. In 1979, they implemented it on a full-scale trial in Glasgow (D.I. Robertson and R.D. Bretherton, 1991). SCOOT uses both stop-line and advance detectors, which are placed typically 150 to 1,000 feet (50 to 300 meters) upstream of the stop line, measuring vehicles leaving the upstream detector. The advance detectors provide a count of the vehicles approaching at each junction. SCOOT also provides queue length detection and estimation. Under the SCOOT system, green waves can be dynamically delayed on a "just in time" basis based on the arrival of vehicles at the upstream detector. It allows extra time to be allocated to the previous green phase, where warranted by heavy traffic conditions. SCOOT controls the exact green time of each phase on a traffic controller by sending “hold” and “force-off” commands to the controller.

The SCOOT model utilizes three optimizers: splits, offsets, and cycle. At every junction and for every phase, the split optimizer will make a decision as to whether to make the change earlier, later, as due, or prior to the phase change. The split optimizer implements the decision, which affects the phase change time by only a few seconds to minimize the degree of saturation for the approaches to the intersection. During a predetermined phase in each cycle and for every junction in the system, the offset optimizer makes a decision to alter all the offsets by a fixed amount. The offset optimizer uses information stored in cyclic flow profiles and compares the sum of the performance measures on all the adjacent links for the scheduled offset and the possibly changed offsets. The benefits obtainable by SCOOT installations were documented in several studies (M. V. Mazzamatti, 1998). However, SCOOT was also criticized for its stepwise change of control parameters that results in a relatively slow adaptation process (B. Friedrich, 2002).

2.2.2 SCATS

The Sydney Coordinated Adaptive Traffic System (SCATS) was developed by the Roads and Traffic Authority (RTA) of New South Wales, Australia (A.

G. Sims and K. W. Dobinson, 1980; P. R. Lowrie, 1982). SCATS uses a split plan selection technique to match traffic patterns to a library of signal timing plans and scales those split plans over a range of cycle times. SCATS gathers data on traffic flows in real-time at each intersection. These data were fed to a central computer via the traffic control signal. The computer makes incremental adjustments to signal timing based on second by second changes in traffic flow at each intersection. SCATS performs a vehicle count at each stop line and measures the gap between vehicles as they pass through each junction. As the gap between vehicles increases, green time efficiency for the approach decreases, and SCATS seeks to reallocate green time to the greatest demand. SCATS selects a timing plan on the controller, and thus the locally actuated controller uses its inherent gap-out and force-off logic to control the intersection second-by-second. Recently, the benefits of SCATS were documented in a simulation study that considered an arterial of six intersections operated by coordinated fixed-time control (C.J. Wilson et al., 2006).

2.2.3 RHODES

The Real-time Hierarchical Optimized Distributed Effective System (RHODES) uses a peer-to-peer communications approach to communicate traffic volumes from one intersection to another in real-time (Head K.L. et al., 1998). By passing the data back and forth over a high-speed communication network, RHODES can predict the impacts of traffic arriving 45-60 seconds upstream and plan for traffic phase sequence and phase durations accordingly. RHODES continually resolves its planned phase timings, every 5 seconds, to adapt to the most recent information. RHODES requires upstream and stop-bar detectors for each approach to the intersections in the network and has a wide variety of parameters that are used to calibrate the traffic model to real-world conditions. RHODES over-rides the local controller by sending “hold” and “force-off” commands to the controller to set the exact duration of each phase.

2.2.4 OPAC

The Optimization Policies for Adaptive Control (OPAC) was developed to support the traffic responsive control of single intersections (N.H. Gartner, 1989). The system uses a predictive optimization with a rolling horizon. This congestion control strategy, which attempts to maximize throughput, adjusts splits, offsets, and cycle length, but maintains the specified phase order. For non-congested networks, OPAC uses a local level of control (at the intersection) to determine the phase durations. OPAC uses a network level of control for synchronization which is provided either by fixed-time plans (obtained offline), or by a virtual cycle (determined online). The levels of local and global influence are flexible and can be adjusted by the traffic engineer. The state of the system is predicated using detectors located approximately 10-15 seconds upstream on the approaches to the intersection. OPAC sends "hold" and "force off" commands to the local controller to set the exact duration of every phase on the signal.

As part of the RT-TRACS project, the OPAC control logic was expanded to include, at the option of the user, an explicit coordination/synchronization strategy that is suitable for implementation in arterials and networks. This version is referred to as Virtual-Fixed-Cycle OPAC (VFC-OPAC) because from cycle to cycle, the yield point or the local cycle reference point is allowed to range about the fixed yield points. The synchronization of phases to terminate early or extend later is allowed to manage better dynamic traffic conditions. VFC-OPAC consists of three-layer control architecture as follows:

Layer 1: The Local Control Layer implements the OPAC III rolling horizon procedure. It continuously calculates optimal switching sequences for the Projection Horizon, subject to the VFC constraint communicated from Layer 3.

Layer 2: The Coordination Layer optimizes the offsets at each intersection (once per cycle). It is done by searching for the best offset of the PS within a mini-network. Since this is carried out in a distributed fashion at each intersection, each SS will, in its turn, also be considered as a PS of its mini-network.

Layer 3: The Synchronization Layer calculates the network-wide virtual-fixed cycle (once every few minutes, as specified by the user). The VFC is calculated in a way that provides sufficient capacity at the most heavily loaded intersections while, at the same time, maintaining suitable progression opportunities among adjacent intersections. The VFC can be calculated separately for groups of intersections, as desired. Over time, the flexible cycle length and offsets are updated as the system adapts to changing traffic conditions.

The literature reported that OPAC can offer remarkable benefits compared with traffic-actuated controllers (N.H. Gartner et al., 2006). OPAC has, however, also been criticized for the missing explicit coordination among the intersections and for its simple traffic model that is error-prone in case of long queues (B. Friedrich, 2002).

2.2.5 MOTION

Method for the Optimization of Traffic Signals in Online Controlled Networks (MOTION) was developed by Busch F. and Kruse G. (1993), and distributed by SIEMENS (2010). In 2002, they further updated the system (Kruse G. and Busch F., 2002). MOTION optimizes the network-wide common cycle length, green splits, offsets and phase sequences every 5, 10 or 15 minutes. MOTION needs strategic detectors at all entries and exits of the network as well as on approaches of intersections, which should be located ideally in sections with a low risk of congestion. Additional detectors for the local level should be located about 40 meters in front of the stop lines. Aggregated detector counts are used to estimate flows of all turnings at intersections and of traffic streams in the whole network.

The original version of MOTION to coordinate intersections used the heuristic method in SIGMA, which was developed by Gabben M. et al. (1988). The two respective optimization criteria are delays and stops, expressed as a normalized index KAPPA. A different source (Busch F., Kruse G., no date) claims that the VERO method by Böttger R. (1972) was used instead, but this is rather unlikely. Mück (2008a, 2008b) reported on latest developments in

MOTION. A new method for the estimation of turning portions at intersections has been implemented. Furthermore, a GA has been implemented to replace the former phase sequence and offset optimization with SIGMA.

2.2.6 BALANCE

Balancing Adaptive Network Control Method (BALANCE) is the other major German adaptive traffic control system. It was developed by Friedrich B. et al., and installed in several German cities (Friedrich, 1997, 2000a, 2000b; GEVAS, 2010). BALANCE has a similar philosophy as MOTION. Aggregated detectors are used as constraints to estimate turning volumes at intersections and on different routes in the network. The estimation employs a dynamic approach based on the correlation analysis of inflow and outflow profiles at intersections (Keller H. and Ploss G., 1987), and the method of entropy maximization (van Zuylen et al., 1980). Based on the queuing model by Kimber and Hollis (1979) and Markov chains, BALANCE estimates queue lengths and delays. BALANCE uses a sequential procedure to optimize offsets described by Braun R. et al. (2008b, 2009).

Friedrich (1997) developed a model-based local control method called Micro BALANCE to be used on the local controllers, and a different local control method was used in general in the BALANCE framework. The most common option is the TRENDS kernel (GEVAS, 2005), a traffic-actuated control method that was also distributed by GEVAS. The original BALANCE made use of a hill-climbing algorithm for optimization, the latest version has been modified by a GA that can optimize cycle length, green splits, phase sequences and offsets at once (Braun et al., 2008a, 2008b).

2.2.7 ACS-Lite

The Adaptive Control Software Lite (ACS-Lite) adapts certain principles which was developed during adaptive control system research and development to use by closed loop systems (Gardner Transportation Systems, 2002). ACS-Lite is developed to reduce the costs to deploy adaptive control systems, by consolidating the adaptive processing into a master control unit that supervises local field controllers. ACS-Lite downloads new split, offset, and cycle parameters to the local controllers every 5-15 minutes in response to changing traffic conditions. ACS-Lite is based on a very simple traffic model that has very few tunable parameters and requires modest calibration. Of all actuated systems, ACS-Lite may be the slowest to respond to rapid changes in traffic flows. ACS-Lite sends cycle, offset, and split values to the local controller. The gap-out and force-off logic of the controller works normally with the updated parameters.

2.2.8 HiCON UTC

HiCON Adaptive Urban Traffic Control System (HiCON UTC) was developed by a Chinese company, Hisense TransTech Co, Ltd. It can connect to Hisense SC series traffic controllers and other compatible controllers. It provides software programming that interfaces for the developer. The system can include 100 control areas, 700 sub-areas, and 5000 controllers. Each area control server can connect to 128 controllers. The collection intervals of traffic flow data can be set up as 1 minute, 5 minutes, 10 minutes or 15 minutes. Traffic condition collection interval is 1 second. The transparent interface supports GPS, video monitoring and VMS connection for multi-system integration.

2.2.9 UTOPIA

The Urban Traffic OPtimization by Integrated Automation (UTOPIA) is the control strategies used in the real-time traffic control implemented over a wide area of Turin since 1984 (Mauro V. et al., 1990). It is a hierarchical decentralized traffic light control system with the objectives of giving absolute priority to selected public vehicles and private traffic optimization in all traffic conditions. The first implementation of UTOPIA was over a significant area of Turin and named “Progetto Torino”, and has been running successfully since 1984. UTOPIA was designed to apply to large scale systems. The global approach is to decompose the whole control problem in a hierarchical decentralized way firstly; define proper functions for the resulting problems, together with rules for their interaction; define techniques and algorithms for solving these issues.

2.2.10 UTCS

The Urban Traffic Control System (UTCS) (TRW, 1973) was implemented in some U.S. cities. FHWA established a test bed in Washington, DC, which served as the prototype for many later systems. UTCS systems implemented in the 1970's and through much of the 1980's possessed the following characteristics: Minicomputer based central computer controls signals with commands for discrete signal state changes. Timing for commands provides at intervals of approximately one second. Signal timing plans are stored in the central computer. Timing plan changes may result from the traffic responsive operation (based on detector inputs from the field), the time-of-day selection, the operator commands (manual), or the computation of volume and occupancy from detector data each minute. This data is used for reports and archival purposes. The data is smoothed with a filter for use with the traffic responsive control algorithm and the graphical display.

2.2.11 Summary of control systems

The control systems have been developing since the 1970s. Besides the adaptive control systems introduced in the above sections, there are some other systems, such as SIGMA (Garben et al., 1988; Schilabbach, 1989), PRODYN (Henry et al., 1983), SPOT(Donati F. et al., 1984), ITACA (Lopez J. and Peck C., 1996), and TACTICS (Siemens, 2012) etc. SCOOT and SCATS are the most widely used locally and internationally. The survey of major adaptive traffic control systems that run in North America and several dozen locations around the world was made by National Cooperative Highway Research Program (Aleksandar Stevanovic, 2010). In their report, the state of practice of adaptive traffic control systems was introduced detailed.

2.3 Offline optimization tools

Several signal timing software packages are available for developing optimal signal timing solutions. Each of these software packages has its unique optimization features such as the optimization objectives: bandwidth based and delay based. Examples of delay based software packages include TRANSYT and SYNCHRO. As self-explained, bandwidth-based software packages intend to maximize the bandwidth when deriving an optimized signal timing solution. Examples of such software include PASSER, MAXBAND, and MULTI-BAND.

2.3.1 TRANSYT

TRAffic Network Study Tool (TRANSYT) (James C Binning et al., 2010) was developed in 1968 by the Transport and Road Research Laboratory (TRRL), UK. It uses a mesoscopic-deterministic model for analyzing and optimizing signal timings on arterials and networks. It uses a combination of exhaustive, hill climbing, shotgun, simulated annealing, and GA-based optimization methods. It is capable of optimizing cycle length, phasing sequence, splits, and offsets. A wide variety of objective functions is also available with the model. TRANSYT 7F uses a delay-based traffic model. In other words, it is primarily designed to select signal timings that produce minimum system delay. During its optimization process, TRANSYT generates second-by-second flow profiles of vehicles on all links in the network. Then, it analyzes these profiles to determine MOEs. TRANSYT treats actuated signals as equivalent pre-timed signals. It also can half or double cycle traffic signals. Although it contains a good delay-based traffic model, TRANSYT bandwidth analysis model is not very good (Texas Transportation Institute, 2003).

TRANSYT calculates the sum of the oversaturated and random delay by using formulae. The “simplified formula” was in TRANSYT version 6, and the revised “less simplified formula” was available optionally since TRANSYT 13. The “simplified formula” is as follows:

$$\begin{aligned}&\text{Random} + \text{oversaturation}\\ &= \frac{T}{4}\left\{\left[(f-F)^2 + \frac{4f}{T}\right]^{1/2} + (f-F)\right\} veh \cdot hours/hour \qquad (2.4)\end{aligned}$$

Where:

f is the average arrival rate on the link (vehicles/hour);
F is the maximum flow that can discharge from the link (vehicles/hour);
T is the duration of the flow condition for which signal timings are being considered (hours).

TRANSYT calculates the number of stopped vehicles by counting the number of delayed vehicles for each delay time by Table 2-2.

Table 2-2 Stops counting in TRANSYT

Vehicle delay (s)	0	1	2	3	4	5	6	7	8	9	≥10
Percent of stop (%)	0	20	58	67	77	84	91	94	97	99	100

The accurate modeling of queues is complicated. TRANSYT uses a time-dependent method of predicting queues, which consider the probability distribution of queue lengths as a function of time.

The performance index (*PI*) in TRANSYT is defined as follows:

$$PI = \sum_{i=1}^{N} (W \cdot w_i \cdot d_i + (K/100) k_i \cdot s_i) \tag{2.5}$$

Where:
N is the number of the links or the traffic streams;
W is the overall cost per average vehicle-hour of delay;
K is the overall cost per 100 vehicle-stops;
w_i is the overall delay weight on the link (or traffic stream) i;
d_i is the delay on the link or the traffic stream i;
k_i is the overall stop weight on the link or the traffic stream i;
s_i is the number of stops on the link or the stream i.

TRANSYT evaluates the PI in monetary terms (£ by default) and the users can change the monetary value by the coefficients *W* and *K*.

2.3.2 SYNCHRO

Synchro (David Husch et al., 2006) is a delay-based program for analyzing and optimizing timing plans for arterials and networks, which was developed by Trafficware Ltd. Its objective function also minimizes stops and delays by applying penalties for these MOEs. Synchro utilizes a graphical user interface to build the network or corridor. Synchro is capable of optimizing cycle lengths, splits, and offsets. In addition, Synchro can partition networks. This feature was used to determine two plausible scenarios for interconnecting systems. Unlike TRANSYT, Synchro's traffic model does not consider platoon dispersion. However, it recommends when to coordinate two adjacent signals by calculating a coordinate ability factor using link distance, travel time, and traffic volumes as input. Synchro optimizes all signal timing parameters for pre-timed and actuated signals, and it applies internally calculated progression adjustment factors for progressed movements. It can also handle double and half cycling of signals. For each cycle length, the program summary report includes numerous MOEs. Synchro has an excellent user interface that provides features to fine-tune easily a timing plan. Furthermore, it provides for data conversion to other popular software.

Synchro uses delay formula in HCM 2000 without the third term to calculate delay, as follows:

$$D = D_1 \cdot PF + D_2 \tag{2.6}$$

Where:
D_1 is the uniform delay;
D_2 is the incremental delay;
PF is the progression factor which is to account for the effects of coordination.

Synchro calculates the PF as follow, which is different with the calculation of PI in HCM 2000.

$$PF = DelayCoord/DelayUnCoord \tag{2.7}$$

Where:
$DelayCoord$ is the uniform delay calculated by Synchro with coordination;
$DelayUnCoord$ is the uniform delay calculated by Synchro assuming random arrivals Level of Service.

Synchro calculates the number of stopped vehicles in the same way with TRANSYT. The formula for the queue length used in Synchro is:

$$Q = \frac{v}{3600} \cdot (r - 6) \cdot \left[1 + \frac{1}{s/q - 1}\right] \cdot \frac{L}{n \cdot fLU} \tag{2.8}$$

Where:
r is the red time (s);

s is the saturation flow rate (vehicles/h);
q is the arrival rate (vehicles/h);
L is the length of vehicle including space between (feet);
n is the number of lanes;
fLU is the lane utilization factor.

If the volume to capacity ratio exceeds 1, the queue length is theoretically infinite. Synchro calculates the queue length as the maximum queue after two cycles, which is:

$$Q' = [v \cdot (c - 6) + (v - s \cdot g/c) \cdot c/3600] \tag{2.9}$$

The PI in Synchro is calculated as follows:

$$PI = [(D \cdot 1) + (St \cdot 10)]/3600 \tag{2.10}$$

Where:
D is the total delay (s);
St is the total vehicle stops.

2.3.3 PASSER

PASSER (Transportation Operations Group, 2009) is a bandwidth-based program for optimizing signal timings for signalized arterials, developed by Texas Transportation Institute. PASSER strictly maximizes bandwidth efficiency by finding the highest value of summing the thru green band divided by twice the cycle length. The heuristic signal timing optimization model of PASSER II is based on a graphical technique, which is simple, efficient, and powerful. It starts by calculating equal saturation splits using Webster's method. Then, it applies a hill climbing approach to adjust splits to minimize delay. Finally, it applies a bandwidth optimization algorithm using the pre-calculated splits for a particular cycle length as input to that model. At the optimization stage, it finds offsets and phase sequences that produce maximum two-way progression. At this stage, PASSER starts by calculating offsets for providing a perfect one-way progression in the A (arbitrarily selected) direction. Then, it minimizes band interference in the B (opposite) direction by adjusting phasing sequences and offsets. After achieving the best band (minimum interference) in the B direction, the program adjusts the two bands according to user-desired options for directional priority. Finally, the program calculates delays, bandwidth efficiency, and attainability. The program performs delay calculations for internal through movements using a macroscopic traffic model that explicitly considers platoon dispersion. Delay calculations for all other movements use the Highway Capacity Manual (HCM) method.

PASSER uses the following equation for estimating control delay for all approaches where random arrivals are assumed. In other words, PASSER does not consider the effects of coordination in its delay model.

$$\begin{aligned} d &= d_1 + d_2 \\ d_1 &= \frac{0.5 \cdot c \cdot \left(1 - {}^{g}/_{c}\right)^2}{1 - \left[min\left(1, {}^{q}/_{Q}\right) \cdot {}^{g}/_{c}\right]} \\ d_2 &= 900 \cdot T \cdot \left[\left(\frac{q}{Q} - 1\right) + \sqrt{\left(\frac{q}{Q} - 1\right)^2 + \frac{4 \cdot (q/Q)}{0.25 \cdot Q}}\right] \end{aligned} \tag{2.11}$$

Where:

d_1 is the uniform control delay, the same with HCM 2000 model, (second/vehicle);

d_2 is the incremental delay (s/vehicle);

g is the effective green (second);

c is the cycle length (second);

Q is the capacity (vehicle);

T is duration of analysis period(hour);

q is the volume (vehicle).

The stops are estimated by the PASSER using the following models:

$$\mathrm{h} = 0.9 \cdot \left(\frac{1-u}{1-y} + \frac{N_0}{q \cdot c}\right) \tag{2.12}$$

Where:

h is the average stops per vehicle;

u is the green split ratio (*g/c*);

y is the flow ratio (*q/s*);

c is the cycle length;

N_0 is the average overflow queue in vehicles, which can be calculated as follows:

$$N_0 = \frac{Q \cdot T_f}{4}\left[(x-1) + \sqrt{(x-1)^2 + \frac{12(x-x_0)}{Q \cdot T_f}}\right] \qquad (2.13)$$

Where:

Q is the capacity in vehicles per hour;

T_f is the flow period in hours (assumed 0.25 h);

x is the degree of saturation (q/Q);

x_0 is $(0.67 + s \cdot g/600)$, where s and g are saturation flow rate and effective green time respectively.

PASSER calculated the queue length by Ackelic's model as follows:

$$N = q \cdot r + N_0 \qquad (2.14)$$

Where:

N is the average vehicles in queue per cycle.

r is the effective red time (s).

The maximum queue length (N_m) is calculated as follows:

$$N_m = N_0 + \frac{q \cdot r}{1-y} \qquad (2.15)$$

2.3.4 TSIS/CORSIM

The Traffic Software Integrated System - Corridor Simulation (TSIS/CORSIM) (Kaman Science Corporation, 1996) is a microscopic-stochastic simulation program. It has two modules: FRESIM for evaluating freeway traffic conditions and NETSIM for evaluating the quality of a selected signal timing plan. TRAFVU is an accompanying graphic animation program. NETSIM can be used to analyze the operation of pre-timed and actuated signals. For a given scenario, CORSIM randomly generates traffic, keeps track of individual vehicles as long as they are in the system, and computes various measures of effectiveness, such as delay, stops, travel times, and fuel consumption). It is believed, that making a simulation run using CORSIM is similar to one-time data collection in the field (Amin E. Elniema, 2011). Thus, it is necessary to make several runs using different random number seeds and averaging the results from those runs before drawing any conclusions. CORSIM was developed using Federal Highway Administration (FHWA) support over a period of several decades and is accepted by transportation professionals as a valid analysis tool. CORSIM does not provide an optimization routine.

2.3.5 Summary of off-line optimization tools

In summary, Synchro has the best user interfaces, and TRANSYT's user interface is complicated. In the report of "Guidelines for selecting signal timing software" made by Texas Transportation Institute, many practitioners dealing with signalized arterials, especially in Texas, prefer not to use TRANSYT (Nadeem A. Chaudhary, et al., 2002). Synchro's optimization speed is fast. The speed of TRANSYT's cycle length optimization algorithm is much lower, especially for the large network. According to the report, even though Synchro delay model does not consider effects of queue spill back and blocking, in most cases it found the best timing plan for arterials. For small arterials, Synchro also produces good progression bands, but this ability severely degrades for larger arterials (Nadeem A. Chaudhary et al., 2002). PASSER's bandwidth optimization algorithm produces the largest progression bands without selecting the largest cycle length. TRANSYT 7F's performance for bandwidth optimization is not excellent. The comparison of parameters of TRANSYT, Synchro and PASSER are summarized in the following Table 2-3.

Table 2-3 Comparison of TRANSYT, Synchro, and PASSER

Parameters	TRANSYT	Synchro	PASSER
Objective	PI(weighted sum of delay and stops) minimize	PI(weighted sum of delay and stops) minimize	delay minimize or green wave band maximize
Optimization algorithm	Hill climbing, Simulated annealing, Shotgun, GA	Not sure	GA and PASSER II

(continuation of previous page)

Network partition	Yes	Yes but not automatically	No
Optimized items	cycle, phase sequence and offset	cycle, phase sequence and offsets	phase sequence and offset
Delay	time-dependent delay model	HCM 2000 model with itself Progression Factor (PF) function	HCM 2000 without considering the effects of coordination
Stops	estimated by the length of the individual delay time	the same with TRANSYT	a model by PASSER
Queue	time-dependent method	a model by Synchro	Akcelik model
Fuel	fuel model	the same with TRANSYT	the same with TRANSYT
Emission	a model by FHA	the same with TRANSYT	No
Level of service	thresholds from HCM 2000	the same with TRANSYT	PASSER defined

2.4 Summary

This chapter reviewed the research on traffic signal timing optimization that has been classified into two categories based on the two suppositions at first. After that, some existing adaptive network control systems including SCOOT, SCATS, RHODES, OPAC, MOTION, BALANCE, ACS-Lite, HiCON UTC, UTOPIA, and UTCS were discussed. At last, several computer optimization tools such as TRANSYT, SYNCHRO, PASSER, and TSIS/CORSIM were presented.

From the literature review, it can be concluded that lots of control systems have been developed, and amounts of modern heuristic optimization algorithms have been applied to the problem of traffic signal timing optimization. The principle of these algorithms is similar that to modify the parameters until the objective satisfy the predetermined convergence condition. The difference is the rule of modifying. In other words, their strategy is the same, what is different is the tactics. Therefore, it is considered if continue researching optimization of signal timing by the heuristic algorithm, will step a “circle” of tactics. So the breakpoint should be the strategy. The drawback of most models is the optimization speed, especially for the network contains hundreds or thousands of intersections. Therefore, the strategy must be available for the large network, and fast enough to realize the real-time optimization. In the next chapters, the proposed optimization strategy will be introduced.

Chapter 3
A sorting model of priority order

When optimizing signal timings within a network, a reasonable start point and searching order may make the near optimal solutions close to the true optimal solutions, or speed up the optimization process. While, not much attention has been devoted so far to the order, in which the intersections are visited. This order will be called in the following as the priority order. Obviously, there are large numbers of different orders, for a moderately large network of 200 intersections there are $200! \approx 7.886 \times 10^{374}$ different ones. TRANSYT is the best tool to demonstrate the effect of priority order since it has a setting of optimization order (priority order). However, the priority orders in TRANSYT are determined by users' experience, which is not rigorous.

Not only TRANSYT concerns on the priority order problem, but also the adaptive traffic control systems, such as SCOOT, SCATS, OPAC, and ACS-Lite need to determine the critical intersection of a network. Therefore, the question comes up. How to determine the critical intersection? How to find the best priority order? How much does the priority order influence the Performance Index (PI) and other Measures of Effectiveness (MOEs)? Is the priority order and the critical intersection fixed all the time or should it change with traffic state?

Much work has been done to find the best solutions in traffic signal planning system, but to the author's knowledge, none of them had been considering the order of the intersections to be optimized. It is generally accepted that the intersection that has the highest saturation degree, or has the largest traffic volume, or the highest number of lanes is the critical or key intersection, and should be optimized at first.

However, is it the best that can be done? Imagine there is a simple network displayed in Figure 3-1. Here, one intersection with the saturation degree of 0.9 is surrounded by the intersections with the saturation degree of 0.5, while another four intersections with the saturation degree of 0.89 are connected with each other. If the priority order is sorted by the intersection's saturation degree, the intersection with the saturation degree of 0.9 will be ranked at the top of the list of priority order. But intuitively, the four intersections with the saturation degree of 0.89 should be in higher priority than the intersection with the saturation degree of 0.9 since the area is congested.

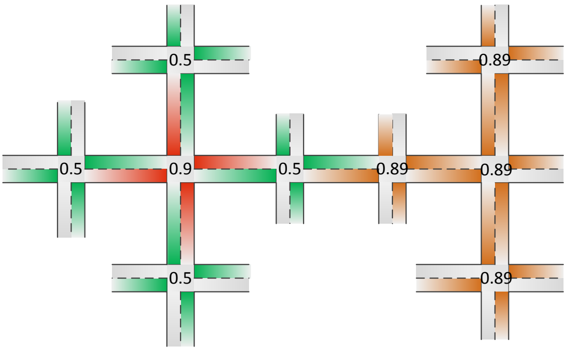


Figure 3-1 Layout of an example network (the numbers are the saturation degrees)

In this chapter, a model will be built that produces the best priority orders according to the traffic state of the network. It has been named as the Sorting Model of Priority Order (SMoPO) (Ting Lu and Peter Wagner, 2013). Also, this method determines the critical intersection of a network, which is simply the first one in priority order.

3.1 Sorting Model of Priority Order (SMoPO)

Based on the discussion above, it is supposed that an intersection's priority order is related to not only the current intersection but also to its immediate adjacent intersections. Two important parameters of the sorting model are defined. The one parameter is named rank index (r), which is the measure of the intersections' priority order. The larger the rank index is, the higher the priority of the corresponding intersetion will be, and the earlier it will be optimized. The other parameter is the belief (b), which is the measure of the dependency of priority order between intersections. Since the priority order is reflexed by the rank index, belief is the dependency of rank index of intersections.

Let r_i represent the rank index of intersection i in the priority orders, which is a number in the interval [0, 1]. Let U_i represent the set of immediate upstream intersections of intersection i; b_{ij} represent the belief of intersection i's rank index depends on its immediate upstream intersection j's rank index. Later on, it will be shown how the entries into the belief matrix can be computed from the geometry and the traffic demand of the network, right now assumed it has been given. Therefore, the following linear equation is assumed to hold for the ranks of the intersections in the network:

$$r_i = \sum_{j \epsilon U_i} r_j \cdot b_{ij} \tag{3.1}$$

The solutions of this equation are the values of rank indexes, which in turn determine the positions in the priority order. The rank index r_i could be understood as the intersection's probability to be at a certain position of the priority order.

Now to determine the belief matrix $\boldsymbol{B}$. As we know, intersections are connected by the traffic flow on the links between them. It is considered that the degree of urgency of the intersection to be optimized depends on its upstream links' degree of the traffic congestion. It means the intersections connected with more congested link should be optimized earlier. The traffic congestion can be quantified by the saturation degree of links, which is the ratio between the arrival traffic flow and the lane capacity. Therefore, the saturation degree is the basis for the entry b_{ij} in the belief matrix. It is also suspected that the traffic volumes and the lengths of the links are the factors of the belief values. However, the numerical experiments which have been performed indicated that, the optimal optimization order has no relationship with links' traffic volumes and lengths, they only relate to the saturation degree. If the link has several lanes corresponding to the different signal phases, the sum of saturation degree of lanes is used as the saturation degree of the link. Let L_{ij} represent the set of lanes on the link from intersection j to intersection i; $x_{ij,l}$ represent the lane's saturation degree, which is computed by

$$x_{ij,l} = \frac{q_l}{\lambda_l \cdot s_l}. \tag{3.2}$$

Where:
q_l is the traffic flow on the lane l, vehicle/ hour;
λ_l is the green splits of traffic flow on the lane l;
s_l is the saturation flow on the lane l, vehicle/ hour.

Then, the degree of saturation of link from j to i is defined as x_{ij}:

$$x_{ij} = \sum_{l \epsilon L_{ij}} x_{ij,l} \tag{3.3}$$

This yields a square matrix $\boldsymbol{X}$ with the elements of x_{ij}. To get the belief matrix from this, the matrix is simply normalized by dividing every element by the sum of all elements in the matrix (Baader Franz and Tobias Nipkow, 1999):

$$b_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} x_{ij}} \tag{3.4}$$

If the number of intersections in the network is n, then the beliefs form a $n \times n$ matrix $\boldsymbol{B}$, with the rows and the columns corresponding to intersections. If there is a direct link from intersection j to intersection i, then the element in the i-th row and the j-th column of the square matrix is $b_{ij} > 0$, if there is no direct link from intersections j to intersection i, $b_{ij} = 0$. The diagonal elements b_{ii} of the belief matrix $\boldsymbol{B}$ are 0, too. All of rank indices of intersections form a non-zero column vector $\boldsymbol{R}$. Therefore, the above equation (3.1) takes the form of an eigenvector equation for the rank index vector:

$$\boldsymbol{B} \cdot \boldsymbol{R} = \boldsymbol{R} \tag{3.5}$$

For example, in Figure 3-2, suppose that the beliefs between intersections are already known, shown as the number on the links.

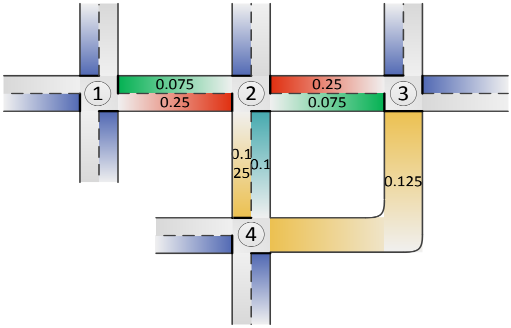


Figure 3-2 A simple case to explain the model

The rank index of intersection 2 (r_2) equals to the sum of the result of multiplying intersection 1's rank index (r_1) by the belief from intersection 1 to intersection 2 *(equals to 0.25)*, and the result of multiplying intersection 3's rank index (r_3) by the belief from intersection 3 to intersection 2 *(equals to 0.25)*, and the result of multiplying intersection 4's rank index (r_4) by the belief from intersection 4 to intersection 2 *(equals to 0.1)*. That is, $r_2 = 0.25 \cdot r_1 + 0.25 \cdot r_3 + 0.1 \cdot r_4$. Therefore, the rank index of all intersections could be computed as follows,

$$\begin{cases} r_1 = 0.075 \cdot r_2 \\ r_2 = 0.25 \cdot r_1 + 0.25 \cdot r_3 + 0.1 \cdot r_4 \\ r_3 = 0.075 \cdot r_2 + 0.125 \cdot r_4 \\ r_4 = 0.125 \cdot r_2 \end{cases} \tag{3.6}$$

This set of equations can be written as:

$$\begin{bmatrix} 0 & 0.075 & 0 & 0 \\ 0.25 & 0 & 0.25 & 0.1 \\ 0 & 0.075 & 0 & 0.125 \\ 0 & 0.125 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} \tag{3.7}$$

In equation (3.5), $\boldsymbol{R}$ is an eigenvector and 1 is its eigenvalue for $\boldsymbol{B}$. But what should be interested is the dominant eigenpair, which can be computed by mathematical software. The elements of the dominant eigenvector $\boldsymbol{R}^*$ are the values of true rank index of intersections in the network. Finally, the element values of $\boldsymbol{R}^*$ are sorted in descending order to obtain the optimal priority order.

3.2 Case studies

The sorting model has been tested on several networks in TRANSYT-14, two cases are presented here. The first one is an arterial consisting of four intersections, the one used by Park et al. (1999). The second one is the network with six intersections used by Allsop and Charlesworth (1977). There are $\prod_{n=1}^{4} n = 24$ feasible priority orders for the first network, which have been enumerated here to evaluate the effectiveness of the proposed model. The number of feasible priority orders for the second network is $\prod_{n=1}^{6} n = 720$, which is too much to be enumerated. So instead a Monte Carlo method has been used to generate a certain number of comparison schemes. Both cases chose Hill-climbing optimization process. In TRANSYT, the time segment and length was set to be 15min and 4 time segments, so the modeled time period is 60min.

3.2.1 Case 1

The basic layout of the arterial was given in Figure 3-3. The spacing between intersections in the arterial was 400 m. All edges along the arterial direction were designed to have one full lane for through and right-turning traffic and an exclusive left-turning bay of 30 m. The free flow speeds were set to be 64.4 km/h for arterial and 48.3 km/h for side streets. The saturated flow rate for all lanes in the network was 1800 vehicles/h. All intersections had four phases. The phase 1 was for the through and right-turn movements on the arterial. The phase 2 was for the left-turn movement on the arterial. The phase 3 of intersection 1 and 3 was for the through and right-turn movements on the side street, and of intersection 2 and 4 is for all movements on the western approach. The phase 4 of intersection 1 and 3 was for the left movement on the side street, and of intersection 2 and 4 is for all movements on the eastern approach. The phase to phase intergreen time was set to be 5s. All intersections were single cycling, and the range of network cycle time was [40, 160] (s) and the increase step was 2s when using Cycle Time Optimiser (CYOP) tool in TRANSYT. The O-D matrix of the network (the unit is vehicles/hour) was shown in Table 3-1.

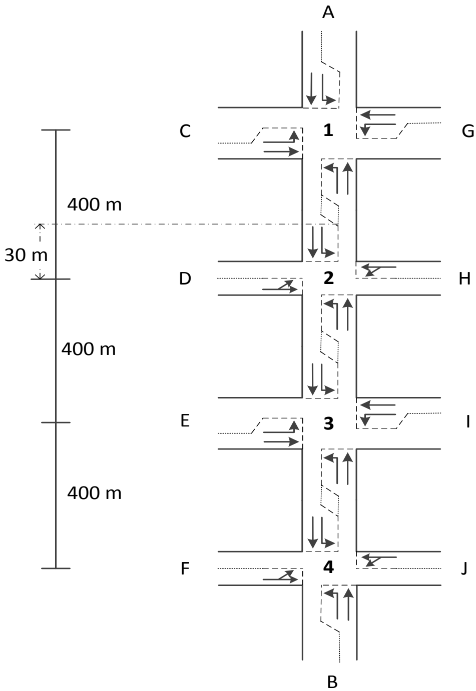


Figure 3-3 Layout for Park's test network

Table 3-1 Origin-Destination demand for Park's test network

O \ D	A	B	C	D	E	F	G	H	I	J	Sum
A	0	210	70	35	35	35	210	35	35	35	700
B	210	0	35	35	35	210	35	35	35	70	700
C	158	18	0	0	9	9	315	0	9	9	527
D	35	9	35	0	0	9	35	210	9	9	351
E	35	18	35	18	0	18	35	35	315	18	527
F	0	35	18	18	18	0	18	18	18	210	353
G	53	53	315	18	18	18	0	18	18	18	529
H	18	35	9	210	18	18	9	0	18	18	353
I	18	105	9	9	315	26	9	9	0	26	526
J	9	105	0	9	9	210	0	9	0	0	351
Sum	536	588	526	352	457	553	666	369	457	413	4917

The optimal priority order by the Sorting Model of Priority Order (SMoPO) yielded 2-3-4-1 (scheme 1). The signal timing and PI value was given in Table 3-2.

Table 3-2 Signal timing with the corresponding PI value

Cycle (s)	Performance Index (£ per hour)	Intersection	Start time				Offset (s)
			Phase 1	Phase 2	Phase 3	Phase 4	
94	2705.77	1	1	36	53	80	0
		2	93	36	48	70	92
		3	0	40	52	79	93
		4	90	31	47	68	89

If taking the Measures of Effectiveness (MoEs) including Performance Index (PI), mean delay and fuel consumption of the scheme by the Sorting Model of Priority Order (SMoPO) (the first scheme) as the reference values, then the percentage changes of all other schemes were shown in Figure 3-4. In this figure, the first three schemes were the schemes which obtained by SMoPO with the priority order of 2-3-4-1, by the total traffic volumes sorting method with the priority order of 1-3-4-2, and by the saturation degree sorting method with the priority order of 2-4-1-3. The other schemes were the remainder of schemes of the 24 schemes. The total traffic volumes sorting method means the priority orders of intersections are sorted in descending order by the total amount of traffic volumes of approaches. Namely, the intersection that has largest traffic volume will be optimized firstly, and the intersection that has secondary largest traffic volume will be optimized secondly and so on. Similarly, the saturation degree sorting method means the priority orders are sorted in descending order by the degree of saturation of intersections. It can be seen from the results that the critical intersection by SMoPO and the saturation method was the same, which was intersection 2.

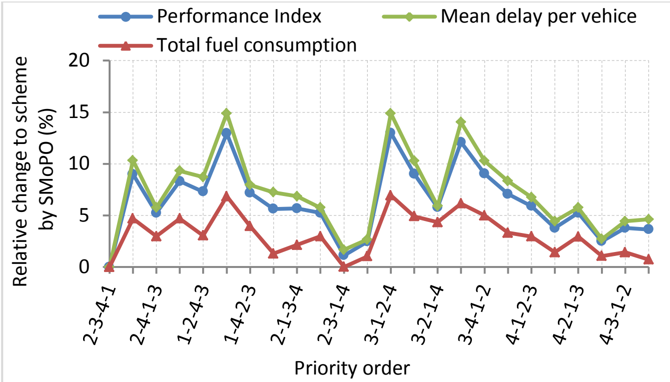


Figure 3-4 Relative changes of three measures of effectiveness compared with the values by the Sorting Model of Priority Oder (SMoPO)

It was indicated in the Figure 3-4 that the scheme by SMoPO with the priority order of 2-3-4-1 (the first scheme) had the smallest (best) PI, mean delay, and fuel consumption. Its PI outperformed the second scheme that was by the total traffic volume rule by 8.98%, and outperformed the third scheme that was by the saturation degree rule by 5.24%. Its mean delay per vehicle outperformed the second scheme by 10.32% and the third scheme by 5.76%, and its total fuel consumption outperformed the second scheme by 4.69% and the third scheme by 2.97%. It may be noticed that the scheme with the priority order of 2-3-1-4 was the second optimal order. The MoEs of this scheme was quite closed to MoEs of the scheme by SMoPO. It was reasonable because they had the same first two optimized intersections that are intersection 2 and 3. It indicated that the higher priority intersections created higher influence to the network's MoEs. From these results, it could be concluded that the priority order by the saturation degree sorting method had better effectiveness than by the total traffic volume sorting method, and the priority order computed by SMoPO had the best effectiveness.

3.2.2 Case 2

The layout of the network and the configuration of signal phases at each intersection was given in Figure 3-5, which was adapted from Allsop (1977). The O/D-matrix was given in Table 3-3. All intersections were single cycling, and the range of network cycle time was set to be [40, 180] (s) and the increment was 2s. The intergreen time was set to be 5s.

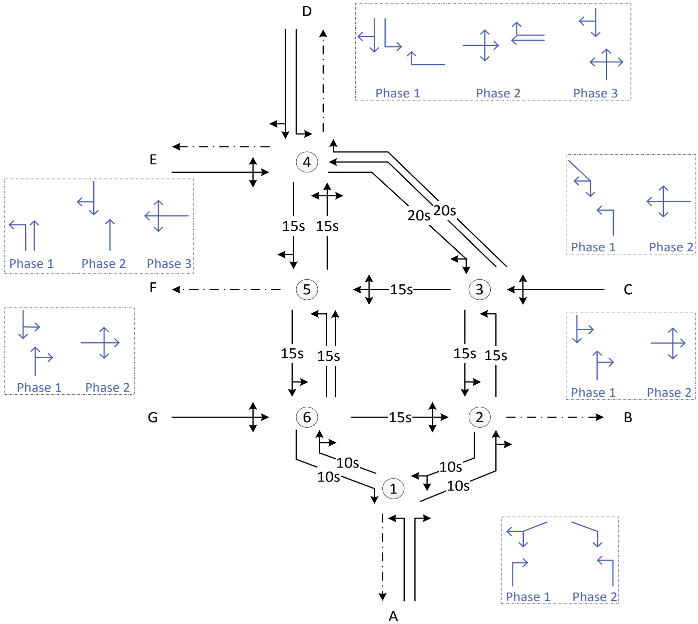


Figure 3-5 Layout for Allsop's test network

Table 3-3 Origin-Destination demand for Test Network in Vehicles/hour

To / From	A	B	D	E	F	Sum
A	0	250	700	30	200	1180
C	40	20	200	130	900	1290
D	400	250	0	50	100	800
E	300	130	30	0	20	480
G	550	450	170	60	20	1250
Sum	1290	1100	1100	270	1240	5000

In order to find a good priority order, the Monte Carlo method was performed as follows:

STEP 1: Initialize by setting the iteration counter k to 1, and set Performace Index value $PI = PI^{(1)}$.

STEP 2: Generate a $\prod_{n=1}^{6} n \times 5\% = 36$ solutions $x_1 \ldots x_{36}$ randomly by the probability of each intersection at each position of priority order obeying the uniform distribution.

STEP 3: Run the 36 solutions in TRANSYT and get PI of each solution. Sort the solutions in ascending order by their PI values, and select the lowest five solutions. Denote the best (lowest) solution's PI value by $PI^{(1)}$.

STEP 4: Generate 17 solutions $x_1 \ldots x_{17}$, whose probability distribution of first position obeys the first position's probability in the five solutions selected in the preceding step. Plus to the best solutions, there is a new set of solutions containing 18 solutions.

STEP 5: Increase k by 1, and repeat 3) and 4) until the maximal iteration times or $PI^{(k+1)} - PI^{(k)} < \varepsilon$.

Because each of these individual orders must be entered into TRANSYT manually, the limited solutions were created and selected as iterated ones. The optimal priority order by the SMoPO method was 5-6-2-1-4-3, with a network PI value of 6651.71 £/h. The priority order by the Monte Carlo method was 5-4-3-2-1-6, by the intersection's saturation degree sorting method was 5-6-1-2-4-3, and by the intersection's total traffic volume sorting method was 6-2-1-3-5-4. It indicated the critical intersection computed by SMoPO, Monte Carlo method, and the saturation degree method was same, which was intersection 5. The signal timing by each priority order was optimized by TRANSYT, shown as Table 3-4. The TRANSYT optimizer has two steps, the first one is for the net's cycle time, the second one is for the splits and offsets. Therefore, the different priority order may lead to the different net cycle time, splits or offsets. For instance, in this case, the net cycle time, splits, and offsets were the same for the priority orders of 5-4-3-2-1-6 (Monte Carlo) and 5-6-1-2-4-3 (Saturation degree). However, they were different for the priority orders of 5-6-2-1-4-3 (SMoPO) and 6-2-1-3-5-4 (Traffic volume). The signal timings were the results of running the TRANSYT optimizer in the same optimization range and settings.

Table 3-4 Optimized signal timing by each priority order

Method	Priority order	Cycle (s)	Intersection	Start time			Offset (s)
				Phase 1	Phase 2	Phase 3	
SMoPO	5-6-2-1-4-3	84	1	6	52		0
			2	9	43		3
			3	3	37		81
			4	76	23	51	70
			5	34	62	1	28
			6	81	47		75
Monte Carlo	5-4-3-2-1-6	78	1	4	47		0
			2	6	38		2
			3	1	33		75
			4	69	20	46	65
			5	29	55	76	25
			6	73	41		69
Saturation degree	5-6-1-2-4-3	78	1	10	53		0
			2	12	44		2
			3	7	39		75
			4	75	26	52	65
			5	35	61	4	25
			6	1	47		69
Traffic volume	6-2-1-3-5-4	70	1	0	39		0
			2	1	30		1
			3	64	23		64
			4	53	8	32	53
			5	21	45	63	21
			6	58	31		58

The measures of effectiveness of each method were compared in Figure 3-6. From this figure, the priority order computed by the SMoPO was demonstrated to be the best priority order again. The PI of the scheme by Monte Carlo method, saturation degree rule, and traffic volume rule respectively were 6787.2 ￡/hour, 6787.2 ￡/hour and 7096.63 ￡/hour. It meant the PI by SMoPO outperformed the Monte Carlo method, the saturation degree rule, and the traffic volume rule by 2.04%, 2.04%, and 6.69%. The mean delay by SMoPO, Monte Carlo method, the saturation degree method, and the total traffic volume method were respectively 71.73 s/vehicle, 73.56 s/vehicle, 73.56 s/vehicle, and 77.69 s/vehicle. It meant the SMoPO outperformed in sequence the others by 2.55%, 2.55%, and 8.31%. Also, their fuel consumptions were 1191 Liter/hour, 1205 Liter/hour, 1205 Liter/hour, and 1243 L/hour. It meant SMoPO outperformed in sequence the others by 1.15%, 1.15%, and 4.40%.

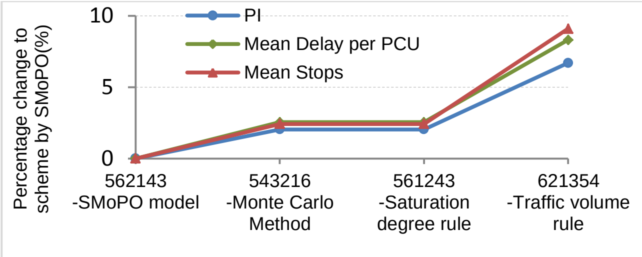


Figure 3-6 Relative changes of measures of effectiveness compared with the values by the Sorting Model of Priority Oder (SMoPO)

It may be noticed that the schemes by the Monte Carlo method and the saturation degree rule had the different optimization orders, but the same MoEs. That is because the two schemes got the same timing plans despite the different optimization orders. It indicated that the different optimization orders may generate the same signal timing plans, as a result, the same MoEs. It also indicated that the method of using saturation degree as a rank criterion may generate a better optimization order, but, in general, cannot generate the best optimization order.

It should be noted that the approach above had computed the different cycle times. So it can be argued that the improvements of SMoPO were resulted from the longer cycle length. Therefore, the same cycle length was set for the different priority orders in TRANSYT, and only the second step optimizer (for splits and offsets) was run. The mean delay of the different priority orders were shown in Figure 3-7.

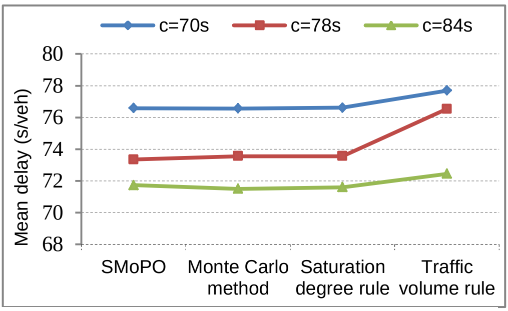


Figure 3-7 Mean delay of the different priority orders in same cycle time

From the Figure 3-7, it could be seen that: 1) a larger cycle time led to a smaller delay time. 2) When the cycle time was fixed in the different methods, the fourth method (the traffic volume rule) performed worse than the other three methods that had close performance.

3.3 Summary

In this chapter, a novel method to compute an optimal priority order in a network, Sorting Model of Priority Order (SMoPO), has been proposed. It takes into account the intersection's location in the network that is the network's topology and the traffic on the links. By using SMoPO, a priority order can be acquired so that more important intersections in the sense of a network will be optimized earlier. Firstly, the sorting model of optimization model was introduced; secondly, two test cases were used to verify the method.

In the two cases, SMoPO turned out to compute a priority order which led to better PI. In the first case, when compared with the scheme obtained by a better greedy algorithm named the saturation degree sorting method, the SMoPO minimized the network PI value by 5.24%, the mean delay per vehicle by 5.76%, the travel time by 4.63%, and the fuel consumption of all vehicles by 2.97%. In the second case, the MoEs of the scheme by SMoPO with the priority order of 5-6-2-1-4-3 were smaller than the other comparison schemes, which were computed by the Monte Carlo method, the saturation degree sorting method, and the traffic volume sorting method. Therefore, the conclusion can be drawn that SMoPO can generate a better optimization order than the other methods, and it is an excellent tool to help to find true optimal signal plans through optimizing the priority order.

In the next chapter, how to use the intersections' priority order to partition an urban network into some subnets will be discussed. Since the model SMoPO is the one component of the dynamic network optimization approach, the model's sensitive analysis will be considered in the flowing chapters with the other components together.

Chapter 4
Network partition strategy

A transport system may consist of several to hundreds or even thousands of intersections to be controlled. As such, one requirement in network-wide signal optimization or signal coordinated control is to partition such a network into smaller subnets that can be controlled independently. This process is named as the network partition.

There are some reasons for the necessity of the network partition.

1) It is time-consuming to compute an optimal signal timing plan if the network contains too many intersections since the optimization time is super-linearly in the number of intersections. For instance, the time that TRANSYT 14 optimizes the signal for a network with six intersections by the simplest optimization algorithm, the hill climbing algorithm, is about two hours. As a result, network-wide real-time signal optimization may be impossible. Therefore, partitioning of a network into subnets makes better use of available computation time.

2) Various parts of the network have different traffic characteristics. For example, the Central Business District (CBD) may contain two-phase signals with short cycle lengths while the suburban areas may contain eight-phase signals with long cycle lengths.

The network partition is often done in an ad hoc, static fashion. The boundaries chosen are rivers, administrative boundaries, or major arterials or freeways. Based on the cycle time of intersections, for example, the subnet A contains intersections with the signal cycle of about x seconds and the subnet B needs cycle of y seconds. However, traffic states on the roads or intersections are not uniform all the time. For instance, there are considerable difference between rush hours and off-peak hours. So, the network partition should be dynamic with traffic states. Secondly, the network partition should be an integral part of real-time urban traffic signal optimization. This idea was proposed by R. J. Walinchus early in 1971 (R. J. Walinchus, 1971). The process of real-time urban traffic control is shown in Figure 4-1. The objective of the network partition and the network signal optimization should be consistent. On the other hand, research on the network partition often concerned only about dividing a network into subnets without considering the subsequent signal optimization.

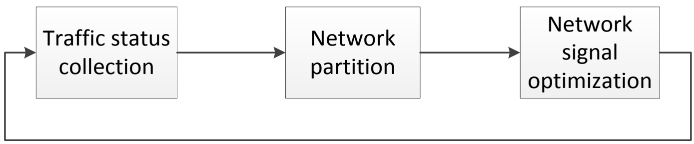


Figure 4-1 Process of real-time urban traffic control

4.1 Review of research on network partition

The network partition has been proven to be an effective technique for developing coordinated signal timing plans, and it has received more attention recently (Zong Tian et al., 2007).

The earliest work in the field of network decomposition was done by R. J. Walinchus in 1971 (R. J. Walinchus, 1971) with the increasing demands for more efficient traffic control. In his paper, the subnet was defined by two steps. The first step was to determine the candidate intersection for consideration as part of a separate sub-network by taking “offset error” or “weighted offset error” as the criteria. The second step was to group candidate intersections into a sub-network by grouping methods, which were pseudo real-time definition, rectangular subset, and connectable set.

H. Nathan Yagoda et al. (1973) proposed partitioning a network by the coupling index (CI) which was defined to be proportional to the traffic volume (q), and inversely proportional to the link length (l), which is

$$CI = q/l. \tag{4.1}$$

The bigger the CI value is, the more desirable to coordinate two intersections will be, and vice versa. Once an CI value map was computed, a threshold was defined such that all the links with coupling index no larger than the threshold were assumed to be broken, and the network was subdivided along these links. His paper was the first paper to decompose urban network by a precise mathematical model. Besides, his paper combined the road geometrical characteristics and traffic volumes into a model, which can be used to do network decomposition in real-time.

Edmond Chin-Ping Chang's paper (1985) indicated that there were two factors to determine whether the intersections need to be coordinated or not. They are the distance between the adjacent intersections, and the imbalance of traffic volumes that is the percentage of left-turn volumes, right-turn volumes, and straight volumes. By combining the two concepts, a model of interconnection desirability was built. On the basis of his model, Hu Hua et al. (2010) and Ma Wanjing et al. (2009) built the new models, in which used the link travel time instead of the link distance in Edmond's model.

Liang-Tay Lin and Shou-Min Tsao (2003) designed a search algorithm to decompose the urban network. The criterions used in the network decomposition involved congestion index, critical block length, traffic level of service, and continuation of traffic movements. Yiming Bie et al. (2011) developed a correlation degree model between two adjacent intersections by the affecting factors that were examined in Liang-Tay Lin's paper.

The program package, Synchro, partitions networks by calculating a parameter named the Coordinatability Factor (CF) for each intersection. The CF is a measure of the desirability of coordinating the intersections. Any intersection with a CF above the threshold value will be put into the same zone. The CF is computed as

$$CF = Max(CF1, CF2) + Ap + Av + Ac. \tag{4.2}$$

Where: $CF1$ is the initial coordinatability factor from the travel time; $CF2$ is the initial coordinatability factor from volume per distance; Ap is the platoon adjustment; Av is the volume adjustment; Ac is the cycle length adjustment (David Husch et al., 2006).

The software TRANSYT uses a parameter, the Mean Modulus of Error (MME), to select links, on which coordination of signals is not very significant and would therefore be suitable for the location of subnet boundaries. The MME is in the range between 0 and 2. A general rule of thumb is that for a MME of less than 0.3, the link may not be worth considering for coordination.

The SCOOT system decides which nodes should be in the same region by taking into account the benefits of coordination. SCOOT can provide the user with information to assist in making the decision of subnets but does not automatically decide by itself. The SCATS uses a static network decomposition method based on a simple index of integration or disjunction of subareas which is rooted in the differences between cycle lengths.

Hook and Albers (1999) proposed and compared three different approaches of determining subnets in signal progression using five randomly chosen links in the City of Fort Collins as a case study. Besides the Synchro partition model, the other two models were Coupling Index (CI) model and Strength of Attraction (SoA) model. The Coupling Index model states that the attraction between two bodies was proportional to their traffic volume (q) and inversely proportional to the length squared (l^2). The formula to calculate the Coupling Index (CI) was given as:

$$CI = q/l^2 \tag{4.3}$$

It can be done simply: the higher the CI is, the stronger the need to coordinate the adjacent intersections will be. In principle, there was no absolute CI that coordination should or should not occur, but a rule of thumb was given. If $CI < 1$, then there was no need to coordinate; if $1 \leq CI \leq 50$, then coordination was desirable; if $CI > 50$, then the coordination was critical. In a certain sense, this model is similar to the model put forward by H. Nathan Yagoda et al. (1973). The difference between them is that in Yadoda's model, the CI was inversely proportional to the length, here it was inversely proportional to the square of the length.

The other model, Strength of Attraction (SoA), was a function of the platoon interference (I), link traffic volume (q), link travel speeds (v) and link length (l). The formula for calculating SoA is show as bellow:

$$SoA = I \cdot q \cdot \left(\frac{v}{l}\right)^2 \tag{4.4}$$

Clearly, platoon dispersion depends strongly on the roadway situation, therefore a platoon interference factor (I) was employed in the model. Hook and Albers recommended to use $I = 2$ for roadways without parking, $I = 1.5$ for roadways with parallel parking, and $I = 1$ for roadways with angled parking. Again, there was no absolute SoA to determine when coordination makes sense. As a rule of thumb, they recommend the following: If $SoA < 0.5$, then there is no need to coordinate; if $0.5 \leq SoA \leq 2$, then the coordination is desirable; if $SoA > 2$, then the coordination is critical.

The experimental results of five links got by Hook and Albers from these three methodologies differ slightly. Some lessons learned were:

1) There was no absolute best factor for determining the subnets occur since each method gives about the same result, the simpler methods were just as valid as the complicated ones.

2) Rather than evaluating regions of a city, it was sometimes useful to coordinate the corridors. For example, some cities have major north-south and east-west corridors, and each corridor can be coordinated separately for optimal cycle length instead of partitioning a city into regions.

3) Often the optimal common cycle length was shorter than the cycle length for all of the intersections satisfied for saturation degree requirements. For instance, if one intersection in the subnet is oversaturated by the optimal common cycle length, then it is better to

allow the oversaturated intersection to run free and coordinate the other intersections.

4) School zones affected the progression since there is large pedestrian traffic so that they can be the logical subnet boundaries. Fire stations signals do not affect progression that much.

5) Be careful in turning movement counts that only measure flow through the intersection.

6) As in aspect of engineering, judgment and experience were the best tools.

Fan W. and Tian Z. (2010) also did the comparison work of these partition methods, and they got the same partition results with Hook and Albers that three different methodologies differed only slightly in their outcome.

Other approaches in literature include: Mo Hankang etc. (2002) based on route guidance; Yun Meiping etc. (2003) subarea districting in incident management systems; Gui Yufeng etc. (2010) using unsupervised classification methods; Li Chungui etc. (2010) based on back propagation neural network.

4.2 Working principle of the proposed strategy

The working principle of the network partition is the deep first search (DFS) for all of the feasible intersections which need be coordinated in the sequence of the priority order. First of all, it is assumed that the priority order of each intersection in the network has been worked out by the model in Chapter 3. Secondly, intersections are searched in the sequence of the priority order to question whether or not they need to be coordinated, and be assigned in the same subnet. This search is done until all intersections are assigned to subnets.

In what follows, the intersection that is currently under consideration is named as the main intersection. In the figures of following alternatives, the main intersection is always intersection i (marked in red), and its adjacent intersections are intersection j and k (marked in black).

Alternative I:

If the main intersection and its adjacent intersections have not been assigned to subnets, assign them into a new subnet, and coordinate all adjacent intersections with the main intersection. For example, in Figure 4-2, it has been known that the main intersection and its adjacent intersections are not assigned to any subnets (filled in solid color), and there is an existing subnet, which is subnet m. Therefore, intersection i, j, and k are assigned into a subnet $m+1$(the area marked in orange), and the coordinate links are the link between intersection i and j ($L_{i,j}$), and the link between intersection i with k ($L_{j,k}$) (marked in light gray).

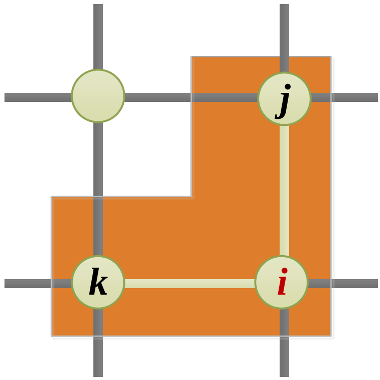


Figure 4-2 Layout of alternative I

Alternative II:

If the main intersection has been assigned to a subnet, but its adjacent intersections have not been assigned to subnets, then assign the adjacent intersections into the subnet, to which the main intersection belongs. For example, in Figure 4-3, intersection i is in the subnet m (filled in stripped pattern background). So its adjacent intersections, intersection j and k, will be assigned into the subnet m (the area marked in blue), and the coordinated links are the link between intersection i and j ($L_{i,j}$), and the link between intersection i with k ($L_{j,k}$).

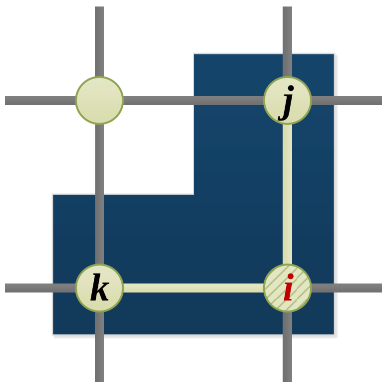


Figure 4-3 Layout of alternative II

Alternative III:

If the main intersection hasn't been assigned to a subnet while one of its adjacent intersections has been assigned to a subnet, assign the main intersection and the other subordinate intersections into the subnet, to which the assigned adjacent intersection belongs. For example, in Figure 4-4, the main intersection and one of adjacent intersections, intersection k or j, haven't been assigned, while the other adjacent intersection, intersection j or k (filled in stripped pattern background), is already in the subnet m (the area marked in blue). So assign intersection i and k, or i and j, into the subnet m, and the coordinated links are the link between intersection i and j ($L_{i,j}$), and the link between intersection i with k ($L_{i,k}$).

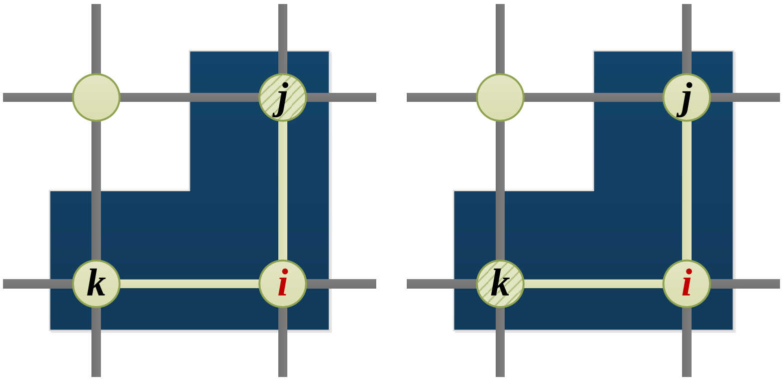


Figure 4-4 Layout of alternative III

Alternative IV:

If the main intersection hasn't been assigned to a subnet while some or all of its adjacent intersections have been allocated to subnets, assign the main intersection into a subnet, to which the subordinate intersection with the highest priority order belongs. For example, in Figure 4-5, the main intersection hasn't been assigned, while the adjacent intersection j (filled in stripped pattern background) is in the subnet $m+1$, and the adjacent intersection k (filled in stripped pattern background) is already in subnet m. And as known that the priority order of intersection j is higher than the priority order of intersection k. So assign the main intersection into the subnet

$m+1$ (the area marked in orange), and the coordinated link is the link between intersection i and j ($L_{i,j}$).

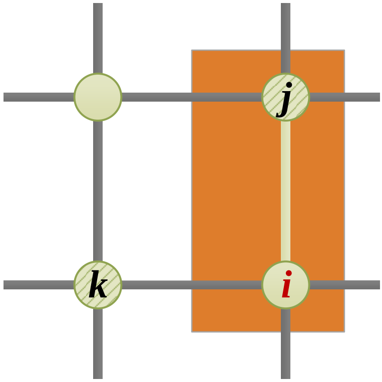


Figure 4-5 Layout of alternative IV

4.3 Algorithm

In the following, the label "k" is used as the counter number of the priority order, so I_k means the intersection which has the priority order k. The parameter "s" is used as the counter number of the subnet, so $I_{s,k}$ means the intersection with priority order of k is in the subnet s. The entire partition process can be presented in the following flow chart, shown as in Figure 4-6.

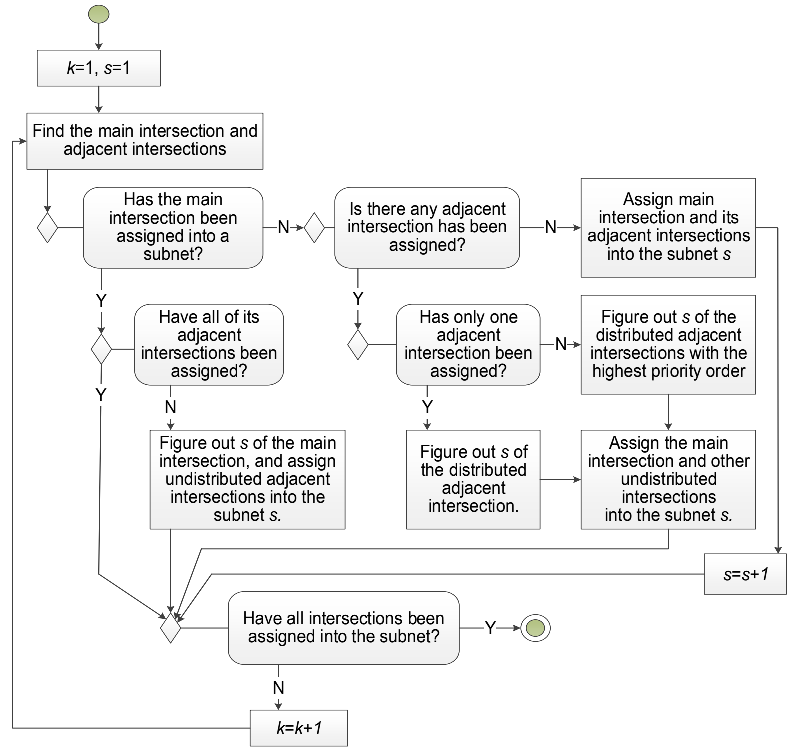


Figure 4-6 Flow chart of the partition strategy

The parameter "p" is a matrix with one row to show whether the intersection has been assigned to a subnet or not. The element of p is either 0 or 1. For instance, $p = [1,0,1,0]$ is translated as there are four intersections in the network, and the intersections with the priority order of 1 and 3 have been assigned to the subnets, but the intersections with the priority order 2 and 4 haven't been assigned to subnets.

The entire partition strategy works as follow:

STEP 0: Initialization. Set counter of optimization order k as 1 and the counter of sub-network s as 1, and set $p_{1\times n}$ as the zero matrix, where n is the total number of intersections.

STEP 1: Iteration. Search I_k and all of its adjacent intersections I_x, where x is a set.

If $p_{1,k} = 1$,

Find s of $I_{s,k}$, and mark $I_{x'}$ as $I_{s,x'}$, where $I_{x'}$ is the set of I_x which has $p_{1,x} = 0$, and set $p_{1,x'} = 1$.

Else if $p_{1,k} = 0$ & $p_{1,x} = 0$,

Mark them as $I_{s,k}$, and set $p_{1,k} = 1$ and $p_{1,x} = 1$, and $s = s + 1$.

Else if $p_{1,k} = 0$ & $p_{1,x} \neq 0$,

Find x of $p_{1,x} = 1$, and $x^* = min(x)$, and find s of I_{s,x^*}, and set $I_{s,k}$ and $p_{1,k} = 1$.

Else,

STEP 2.

STEP 2: Convergence Test. If $\text{sum}(p) = n$, Stop;

Else,

Set $k = k + 1$ and return to STEP 1.

4.4 A hypothetical case

The grid network with nine intersections which shown in Figure 4-7 is used to explain the partition strategy. The number on the intersection expresses its priority order. The circle with solid color background means the intersection has not be arranged into any subnet yet. Once it is set, the circle is changed to the striped pattern background.

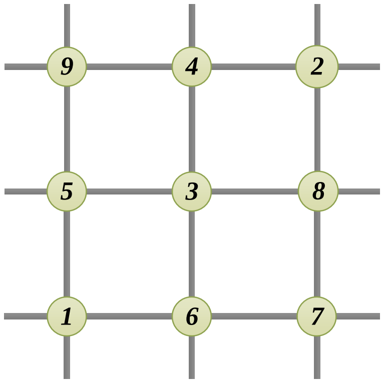


Figure 4-8 Layout and priority order of hypothetical network

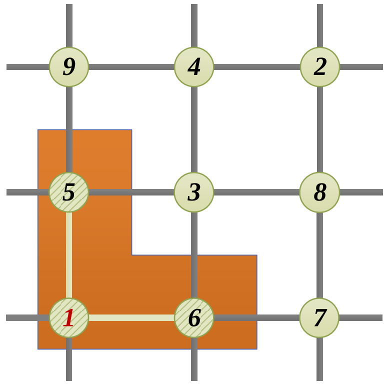


Figure 4-7 Layout after the first search

According to the partition method stated in section 4.2, the intersection with the priority order of *1* (I_1) is the main intersection, and the current subordinate intersections are its direct adjacent intersections, which are the intersection with the priority order of *5* (I_5), and the intersection with the priority order of *6* (I_6). Now, they are assigned to a same subnet, the subnet I, since no subnet has been formed before. This subnet is shown as orange area in Figure 4-8. And the links $L_{1,5}$ and $L_{1,6}$ in light gray are the coordinated links.

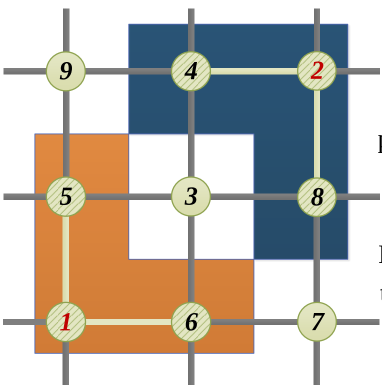


Figure 4-9 Layout after the second search

The intersection with the next priority order is analyzed now. The main intersection is the intersection with the priority order of *2* (I_2) and its adjacent intersections are the intersection with the priority order of *4* and *8* (I_4 and I_8). Because they all are not in any subnet, they are assigned to a new subnet, the subnet II, shown as the blue area in Figure 4-9. And the links $L_{2,4}$ and $L_{2,8}$ in light gray are the new coordinated links.

Next, the intersection with the priority order of *3* will be analysed. It is found the main intersection I_3 hasn't been assigned to a subnet, but all of its adjacent intersections, intersection *4*, *5*, *6*, and *8* (I_4, I_5, I_6, and I_8) have been assigned to subnets. Now the intersection that has the highest priority among all of these adjacent intersections is I_4 . So the main intersection I_3 should be coordinated with I_4. It is figured out that the subnet of I_4 is the subnet II. So the main intersection I_3 is assigned to the subnet II, as shown in Figure 4-10. And the link $L_{3,4}$ in light gray is the new coordinated link.

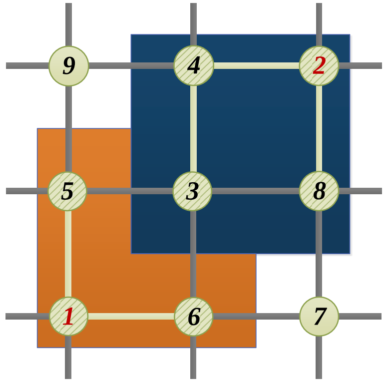


Figure 4-10 Layout after the third search

Now search the intersection with the priority order of *4* (I_4). It is found that the main intersection I_4 and its adjacent intersections with the priority order of *2* and *3* (I_2 and I_3) have been assigned into the subnet II, but one adjacent intersection with the priority order of *9* (I_9) hasn't been assigned. I_9 will be coordinated with I_4, and it is figured out the subnet of I_4 is the subnet II. So the I_9 is assigned to the subnet II, as shown in Figure 4-11. And the link between intersection *4* and *9* ($L_{4,9}$) in light gray is the new coordinated link.

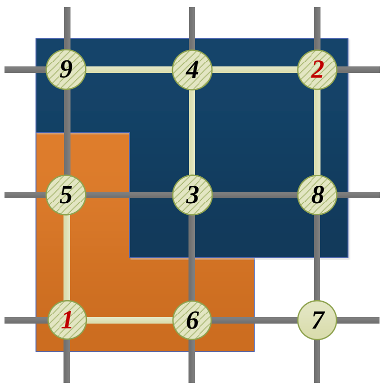


Figure 4-11 Layout after the fourth search

Now search the intersection with the priority order of *5* (I_5). It is found that the main intersection I_5 and its adjacent intersections with the priority order of *1*, *3*, and *9* (I_1, I_3 and I_9) have already been assigned to subnets. So go on searching the intersection with the next priority order that priority order *6*. Now the main intersection becomes I_6, which has been assigned to the subnet I. Its adjacent intersections with priority order of *1* and *3* (I_1 and I_3) have been assigned, but one adjacent intersection with priority order of *7* (I_7) hasn't been assigned. So I_7 need to be assigned to the subnet I which is the subnet of current main intersection (I_6) belongs, as shown in Figure 4-12. And the link between intersection *6* and *7* ($L_{6,7}$) in light gray is the new coordinated link.

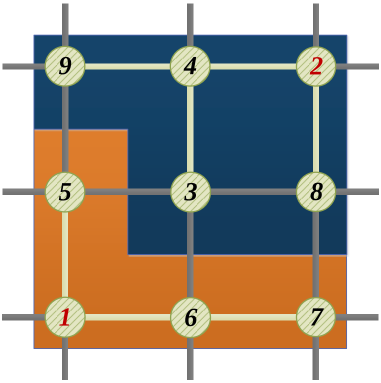


Figure 4-12 Layout after the sixth search

Finally, all of the intersections in the net have been assigned to the subnets that conclude the process.

Chapter 5 Network signal coordination strategy

So far, the model to find the optimal priority order and the algorithm to partition the network to subnets has been proposed. At this point, the priority order of a given network has been established, and a large network has been partitioned into smaller subnets with the help of this priority order. What remains to be done is the signal coordination. Much research work has been done, whose literatures have been reviewed in Chapter 2.

On the one hand, the advancement of technologies makes high-resolution traffic data more readily available. For example, in California, second-by-second returns of loop data can be obtained and archived via using Assembly Bill 3418 (AB3418) (Yafeng Yin, 2008). On the other hand, the computation time to optimize traffic signal grows quickly with the expansion of the network. However, in the proposed strategy, the computation time can be shortened considerably by decomposing the network to subnets.

5.1 The impact of offsets on flow

In this section, what will be discussed is whether or not the relative offset affects the downstream traffic flow. So a simple network containing three intersections is sufficient to research this problem. The detector loop (*L*) was placed on the link between intersection *B* and *C*, as shown in Figure 5-1. The traffic flow recorded by the loop (*L*) need to be analyzed by changing intersection *A*'s offset. Some additional settings to the network include 400m of the link length, 50km/h of the speed limit, 90s of the cycle length, and no turning vehicles.

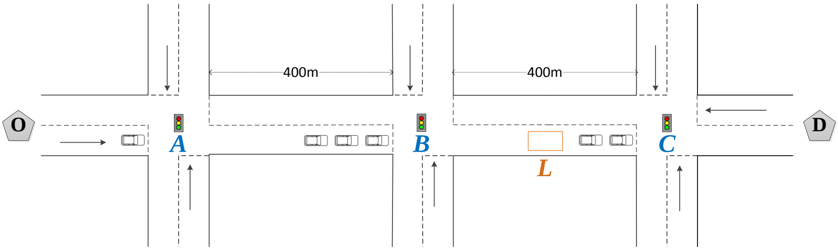


Figure 5-1 Layout of network

The reason why this problem needs to be clarified is that the optimal absolute offsets are converted by the optimal relative offsets in the proposed strategy in section 5.2. If the relative offset can affect the flow, the conversion between relative and absolute is false.

As a matter of practicality, the traffic demand from the origin point (O) in this study was set in the range of [100, 800] with the increment of 100 vehicles. The offset of intersection *A* was changed in the range of [0, 89] (89 equals cycle length – 1) with the increment of 1s. The input origin flows are the value of x-axis, and the detected flows are the value of y-axis, then plot the points in a figure. If these points form a line at an angle of 45 degrees, it means the detected flows are consistent with the input flow. In other words, the relative offset cannot affect

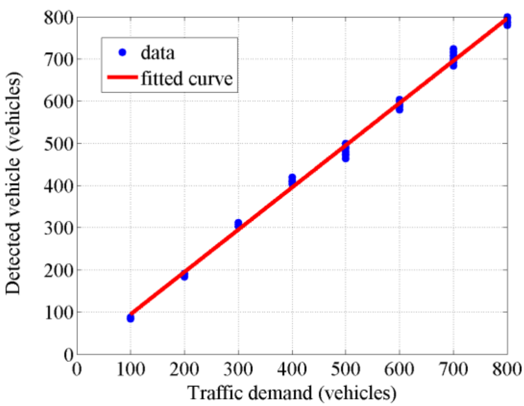


Figure 5-2 Detected traffic flow when offsets change

the downstream flow. Otherwise, it means the offset can affect the flow. The simulation was run in SUMO for 1h computer time, and the result was shown in Figure 5-2.

From the Figure 5-2, it can be seen that all of the points were fitted as the line at the angle of 45 degrees. The coefficient of determination (R^2) equals 0.997. So the conclusion can be drawn that the traffic flow cannot be affected by the upstream intersection’s relative offset.

A similar research was examined within a cellular automata micro-simulation model by Nathan H. Gartner et al. (Nathan H. Gartner and Peter Wagner, 2004). Their result showed that arterial throughput was dependent on offsets and the constituent single intersection limiting capacity. Their conclusion seems to contradict the proposed conclusion here. However, the simulation experiment proposed here was performed in a closed system like a circle, where the density of the system was kept constant for the duration of the simulation running. If the offsets affect travel time (speed), then the flow must change by the Greenshields model, $q = k \cdot v$, which depicts a linear speed-density relationship (Greenshields B.D., 1935). For an open system with constant demand, density and speed must change according to the offsets.

5.2 Optimization strategy

Through network partition strategy in the previous chapter, a network has been partitioned into some subnets. Now, the network signal coordination strategy is the continuation of network partition strategy. The strategy has two steps. The first step is to coordinate the signal timing of intersections inside each subnet separately. The second step is the signal transmission between the adjacent subnets, namely, the signal optimization of the boundary intersections of subnets.

5.2.1 Signal optimization inside the subnet

The working principle of the offsets optimization inside a subnet is to coordinate each intersection pair in the sequence. The intersection pairs are the intersections connected by the coordinated links, which have been marked in the process of the network partition. The optimal offset of an intersection pair is worked out at first, which is called the relative offset. It has been proven that the upstream link's offset cannot affect the relative optimal offset of a downstream link in the last section. So the next step is to convert the relative offsets to the absolute offsets, which are the common meaning of offsets. The method of computing the relative optimal offset between two adjacent intersections will be introduced in Chapter 6.

The intersection that has the highest priority order among intersections in the subnet is named as the key intersection, marked as I_s^*. Where s is the count number of the current subnet. The absolute offset of I_s^* is 0s. If the priority order of the key intersection (I_s^*) is k, then the absolute offset will be written as $\varphi_k = 0s$. By coordinating the intersections connected by I_s^*, the optimal relative offsets of these intersection pairs will be worked out. The absolute offsets equal to the relative offsets, because the adjacent intersections are connected with the key intersection I_s^*. Next, find the intersection which has the second highest priority order in the subnet (supposed its priority order is m), which is the current key intersection, written as I_m. If there are coordinated links connected by I_m, do the coordination for the intersections which are connected by the coordinated links, and work out the optimal relative offsets. If the absolute offset of the current key intersection is already known, which is φ_m, and the relative offset between it and one coordinated intersection with the priority order of i is $\varphi_{m,i}$, then the absolute offset of the intersection which has the priority order of i is φ_i. It is computed by

$$\begin{gathered}\varphi_i = \varphi_{m,i} + \varphi_m \\ \varphi_m = \varphi_i - \varphi_{m,i}\end{gathered}. \tag{5.1}$$

Where:

φ_i is the absolute offset of the intersection with the priority order of i;

φ_m is the absolute offset of the current key intersection;

$\varphi_{m,i}$ is the relative offset between the current key intersection and one coordinated intersection which has the priority order of i.

The first equation is used when the absolute offset of the current key intersection is already known, and the second equation is used when the absolute offset of the current key intersection is unknown.

If there are no coordinated links connected by I_m, then find the intersection with the next highest priority order, and it becomes the current key intersection, and so on. After the optimization for the subnet I, the subnet II (if exists) is optimized using the same strategy, repeat it until all of subnets are optimized. This process was summarized in the flow chart, shown as Figure 5-3.

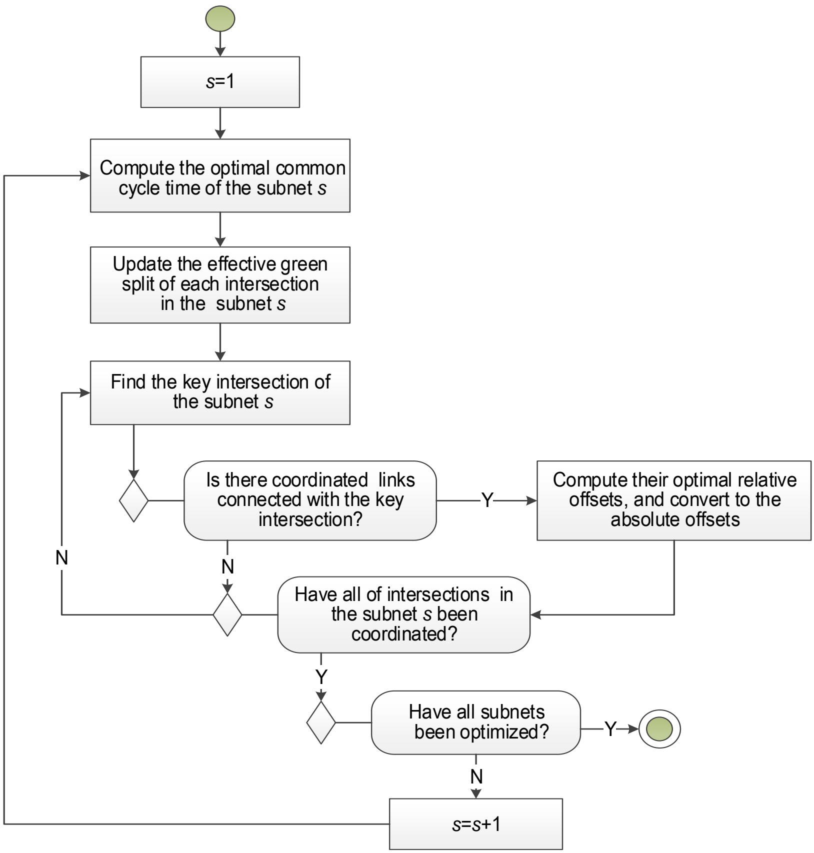


Figure 5-3 Flow chart of signal optimization inside the subnet

5.2.2 Signal transmission between the adjacent subnets

Whether or not a new coordinated link is added will be determined by the common cycle time of the adjacent subnets. If the common cycle time of two adjacent subnets is different, then the present signal timing is the final signal timing. If the common cycle time of two adjacent subnets is the same, a new link needs to be coordinated. The one coordinated boundary intersection is the intersection which has the highest priority order among all of the boundary intersections (supposed it's in the subnet m), marked as I_{B1}^{m}. The other coordinated boundary intersection is the intersection which has the highest priority order among all of boundary intersections connected by I_{B1}^{m}, marked as I_{B2}^{n} (supposed it's in the subnet n). Coordinate these two intersections and work out the optimal relative offset of them, which is written as $\varphi_{B1,B2}$. Now the absolute offset of I_{B2}^{n} will be corrected by $\varphi_{B2} = \varphi_{B1,B2} + \varphi_{B1}$, where φ_{B1} is the absolute offset of I_{B1}^{m}. Then the offsets of all intersections in the subnet n except the intersection I_{B2}^{n} will be modified by

$$\varphi_i^* = \varphi_{B2} - \varphi_j + \varphi_i. \tag{5.2}$$

Where:

φ_i^* is the new absolute offset of the intersection which has the priority order of i in the subnet n;

φ_i is the original absolute offset of the intersection which has the priority order of i in the subnet n;

φ_{B2} is the new absolute offset of the boundary coordinated intersection I_{B2}^{n};

φ_j is the original absolute offset of the boundary coordinated intersection I_{B2}^{n}, since supposed its priority order is j.

Up to now, once signal coordination for the whole network is completed. This signal coordination process will be repeated every time interval according to the optimization frequency (e.g. 30 minutes). Due to the change of traffic states, the updated timing parameters may have a large difference to the previous ones in some periods. Therefore, the small step transmission for less disruption to the traffic is required. If the difference between the updated common cycle length and the previous one is smaller than t, which is a user configurable parameter (for instance 5 seconds), then the control plan is updated directly. If the difference is larger than t, then the common cycle length is changed gradually by t seconds to the updated common cycle length. The process can be summarized in the flow chart, shown as Figure 5-4.

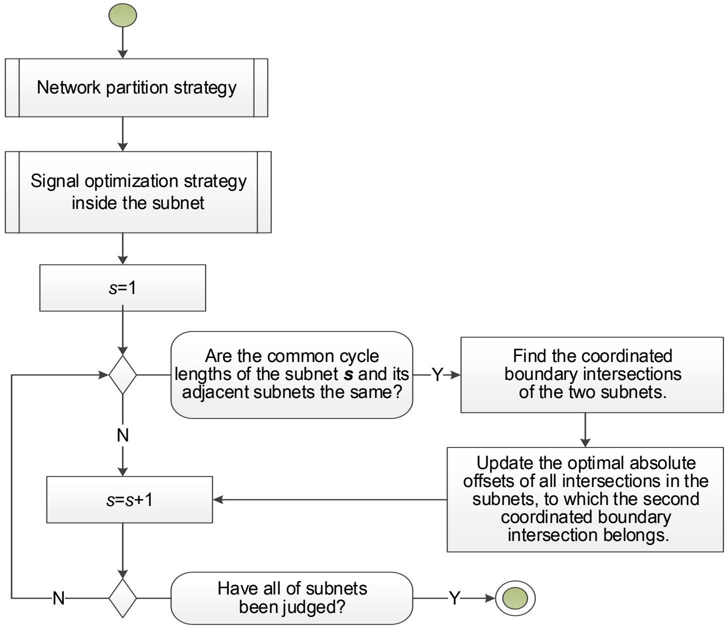


Figure 5-4 Flow chart of signal coordinate between subnets

5.3 A hypothetical case

The hypothetical case that is used in the last chapter continues to be used here to explain the network signal coordination strategy. The grid network has been partitioned into two subnets in Section 4.4. In order to simplify the explanation, it is supposed that the optimal common cycle time of each subnet has been worked out, the green splits of each intersection have been updated, and the optimal relative offset is 6s for every coordinated link. Firstly, the

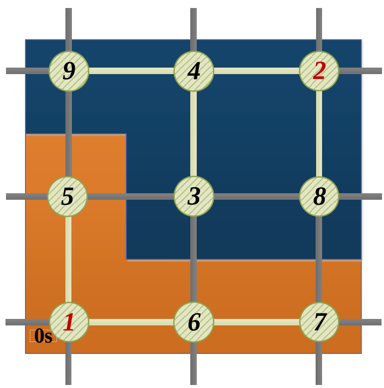


Figure 5-5 Layout with coordinated links and priority order of hypothetical network

intersection with the first priority order is the key intersection of the subnet I (the orange subnet), which is written as I_1^*.The offset of the key intersection is $\varphi_1 = 0s$, as shown in Figure 5-5.

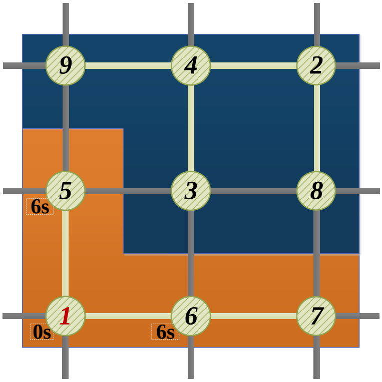


Figure 5-6 Layout after the first search

It can be seen from Figure 5-5, there are coordinated links (in light gray) connected by I_1, which are the link between intersection *1* and *5* ($L_{1,5}$) and the link between intersection *1* and *6* ($L_{1,6}$). It has been supposed that the optimal relative offset for every coordinated link is 6s, that is $\varphi_{1,5} = \varphi_{1,6} = 6s$. So the optimal absolute offsets of intersection *5* (I_5) and intersection *6* (I_6) are $\varphi_5 = \varphi_1 + \varphi_{1,5} = 0 + 6 = 6s$ and $\varphi_5 = \varphi_1 + \varphi_{1,5} = 0 + 6 = 6s$ by equation (5.1), as shown in Figure 5-6.

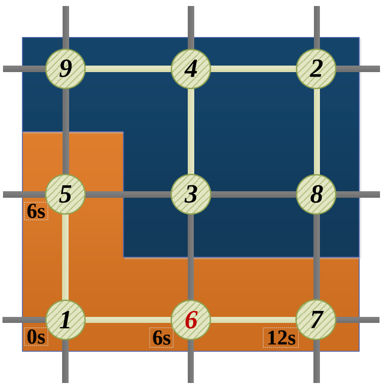


Figure 5-7 Layout after the third search

Now, the current key intersection of the subnet I is intersection *5* (I_5). It is found there are no new coordinated links connected to I_5. So the key intersection of the subnet I becomes intersection *6* (I_6). It can be seen from Figure 5-6, the new coordinated link connected by I_6 is the link between intersection *6* and intersection *7* ($L_{6,7}$). The optimal relative offset between I_6 and I_7 is $\varphi_{6,7} = 6s$, so the absolute offset of I_7 is $\varphi_7 = \varphi_{6,7} + \varphi_6 = 12s$, as shown in Figure 5-7.

At this point, all the intersections in the subnet I have been coordinated, so the intersections in the subnet II are going to be coordinated. By the same process as the subnet I, the key intersection of the subnet II is intersection *2* (I_2^*) and its offset is $\varphi_2 = 0s$. It can be seen from Figure 5-7, the coordinated links connected by I_2^* are the link between intersection *2* and *4* ($L_{2,4}$) and the link between intersection *2* and *8* ($L_{2,8}$). So their optimal absolute offsets are $\varphi_4 = \varphi_2 + \varphi_{2,4} = 6s$ and $\varphi_8 = \varphi_2 + \varphi_{2,8} = 6s$, as shown in Figure 5-8.

The current key intersection of the subnet II is intersection *3* (I_3). It can be seen from Figure 5-8, the coordinated link connected by I_3 is the link between intersection *3* and intersection *4* ($L_{3,4}$). The optimal relative offset between I_3 and I_4 is $\varphi_{3,4} = 6s$, and the absolute offset of I_4 is 6s. So the absolute offset of I_3 is $\varphi_3 = \varphi_4 - \varphi_{3,4} = 0$s, as shown in Figure 5-9.

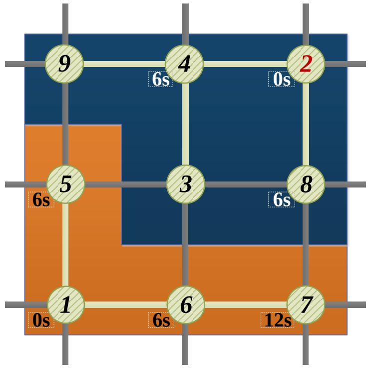


Figure 5-10 Layout after the forth search

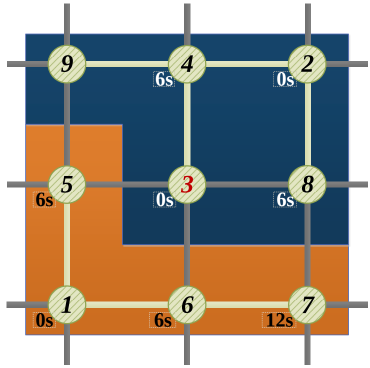


Figure 5-9 Layout after the fifth search

Now, the current key intersection of the subnet II is intersection *4* (I_4). It can be seen from Figure 5-9, the other coordinated link connected by I_4 is the link between intersection *4* and intersection *9* ($L_{4,9}$). The optimal relative offset between I_4 and I_9 is $\varphi_{4,9} = 6s$, and the absolute offset of I_4 is 6s. So the absolute offset of I_9 is $\varphi_9 = \varphi_{4,9} + \varphi_4 = 12s$, as shown in Figure 5-10. Up to now, all intersections in all subnets have been coordinated, and the offset matrix is $\varphi = [0,0,0,6,6,6,12,6,12]$.

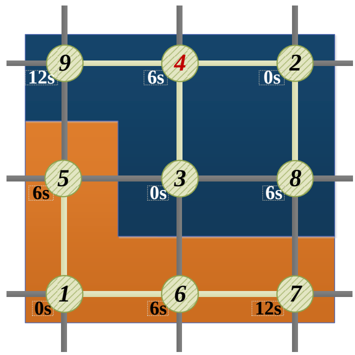


Figure 5-8 Layout after the sixth search

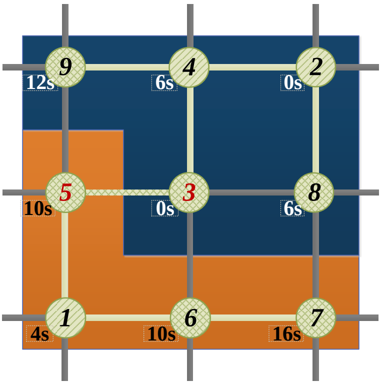


Figure 5-11 Layout with the boundary intersections and coordinated boundary link after the seventh search

Now, all intersections have got optimal offsets. The final task is to judge whether or not the subnets need be coordinated by their boundary intersections, I_3, I_5, I_6, I_7, I_8, and I_9, which are filled in mesh pattern background in Figure 5-11. Supposed that the common cycle length of the two subnets are the same, so the first coordinated boundary intersection I_{B1} is I_5 and the second coordinated boundary intersection I_{B2} is I_3, and the new coordinated link is the link between intersection *3* and intersection *5* ($L_{3,5}$). As you see, if the number of subnets is small, the number of coordinated links between boundary intersections is small too. Then the improvement from the coordination of the adjacent boundary intersections is small while it may take much additional computation time in this step. Therefore, this step could be ignored when implemented in the field, even though the theoretical logic is correct. Supposed the optimal relative offset between the coordinated boundary intersections is $\varphi_{B1,B2} = \varphi_{5,3} = 10s$, so the absolute offset of I_5 is corrected to $\varphi_5 = \varphi_{5,3} + \varphi_3 = 10 + 0 = 10$s. The optimal absolute offsets of other intersections except I_5 in the subnet I (the orange subnet) need to be increased by $10 - 6 = 4$s. The final optimal absolute offsets of all intersections are shown in Figure 5-11.

5.4 Summary

Now the upper level of the network traffic signal optimization, that is the level of the macro traffic control strategies has been introduced completely by the above three chapters. Every time intersections' priority orders are updated, the sub-network distribution and the signal plans will be updated. The flow charts of strategies were designed, and a hypothetical case consisted of nine intersections was employed to explain these strategies step by step.

Chapter 6

A method to compute the optimal relative offset

The computation method of the intersections' absolute offsets on the assumption that the relative offset between each coordinated intersection pair being given was introduced in Chapter 5. In this chapter, how to compute the optimal relative offsets between intersection pairs will be discussed.

After the cycle time c is determined, the green splits of the phases will be distributed in proportion to the corresponding ratio between the flow of critical movement and its saturation flow (y), which is computed by (Evans H. K., 1950):

$$g_i = \frac{y_i}{Y}(c - L) = \frac{y_i}{\sum_{i=1}^{n} y_i}(c - n \cdot l - R). \tag{6.1}$$

Where:
g_i is the effective green split of phase i, the total phase number is n;
y_i is flow ratio of phase i, and Y is the sum of y_i of n phases;
L is the total lost time per cycle, which equals $nl + R$. Here l is the average lost time per phase and R is the all-red time.

In addition, there are minimal green splits (g_{min}) and maximal green splits (g_{max}), $g_{min} \leq g_i \leq g_{max}$. g_{min} often takes into account the shortest pedestrian crossing time which lets a group of pedestrian fulfill once crossing.

g_{max} considers the pedestrian's psychological waiting limit, otherwise, pedestrian safety deteriorates since some pedestrians run red lights.

As we know that the measures of effectiveness (MOEs) of the signal control change when the offsets of the two adjacent intersections change, the objective is to find an offset to make the coordinated links have best (smallest) average delay. Therefore, if the average delay of each offset in the range of [0, cyce-1] (s) can be computed, the optimal offset can be selected from them.

6.1 Review of the existing methods

The methods for optimizing offsets include techniques such as manual adjustments based on field observations, bandwidth maximizing procedures based on time-space diagram concepts, and disutility (delay/stops) minimizing procedures based on platoon dispersion models.

The earliest methods of offset optimization were based on the geometric maximization of bandwidth, sometimes also called the maximization of progression. It was defined by Marsh (Marsh B. W., 1927). The earliest work of using time space-diagrams to design progressive signal systems was written by Petterman (Petterman J.L., 1947). Their computation process seems simple due to restrictions of technology at that time: the traffic engineers did the optimization by hand. Later in 1969, Ficklin and Pontier built the three-dimensional time-space diagram, which was named as "analog traffic model" (Ficklin et al., 1969).

With the advent of the digital computer, some software packages to maximize the green bandwidth appeared. The three most widely used packages are MAXBAND, PASSER, and MULTIBAND. MAXBAND were developed by Little J.D.C. et al. in 1981 (Morgen J.T., 1964; Little J.D.C., 1964; Little J.D.C. et al., 1981). The primary method was a mixed-integer linear programming. MULTIBAND is an extension of the MAXBAND. The improvement was that rather than attempting to maximize bandwidth for the entire arterial, the bandwidth on each segment was independently maximized (Gartner N.H. et al., 1990; 1991). Built upon MULTIBAND, Stamatiadis and Gartner (Gartner N.H., 1996) further developed a MULTIBAND-96 model, which was a network version of MULTIBAND. With MULTIBAND-96, all the signal control variables in a network can be optimized. PASSER was developed at the Texas Transportation Institute (Messer C.J. et al., 1974). Earlier versions of PASSER utilized the principle of interference minimization to achieve the objective (Bleyl R.L., 1967). The current version, PASSER IV, used a mixed integer linear programming method similar to MAXBAND (Chaudhary, N.A., 1993).

In recent years, some other studies were conducted. Park et al. (Park B. et al., 1999) attempted to combine genetic algorithms and mixed integer linear programming to find the optimal means to coordinate traffic signals. Lu et al. (Lu S. et al., 2008) proposed a MAXBAND-Dispersion model by incorporating a traffic flow dispersion module. Their goal was to address one limitation of the MAXBAND model that all vehicles travel at the same speed. Hu et al. (Hu P. et al., 2011) pointed out that an assumption in the "half-integer algorithm" was invalid. They challenged the viewpoint that the lower and upper interferences cannot occur simultaneously at an intersection and proposed an improved algorithm. Papola et al. (Papola N. et al., 1998) proposed an arterial traffic signal coordination model that can generate split solutions. It was found that the differences between the split and un-split solutions were marginal for arterials with a sufficient number of traffic signals. Tian et al. (Tian Z. et al., 2008) assessed the impact of arterial left-turn phase sequence on arterial signal coordination. They found that lead-lag left-turn phase sequence was the most effective and the number of signals also had a significant impact on signal coordination effectiveness. Chao Zhang (Chao Zhang et al., 2014) proposed an asymmetrical multi-band (AM-BAND) model by relaxing the symmetrical progression band requirement in MULTIBAND. Such a relaxation allowed the AM-BAND model to utilize better all the available green times in each progression direction.

The other branch of offset optimization is for the purpose of the delay minimization. So an inescapable problem is the estimation of coordinated delay, which is the delay of coordinated links. Hillier and Rothery (1967) developed a method of synchronizing traffic signals based on vehicle platoon. The arrival rate and service rate were given, and the delay experienced by the

jth vehicle is the horizontal distance $t_2 - t_1$ as shown in Figure 6-1. The queue length experienced by the jth vehicle is the vertical distance. The offset was changed by adjusting the service rate within all values in full range of the cycle, while the degree of saturation was modeled by adjusting the value of the service rate.

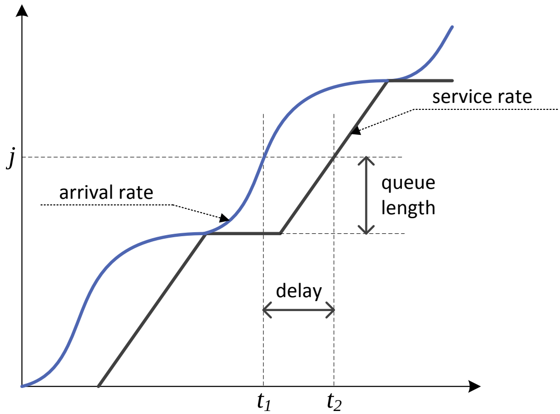


Figure 6-1 Vehicle delay at a signalized intersection by Hiller and Rothery

In 1969, Whiting et al. used delay-offset relationship in management of signal timing plans, and later developed a software package marketed as “GLC Combinations” (Huddart K.W. et al., 1969; Hiller, 1965). The relationships were obtained through a platoon modeling process similar to that used by TRANSYT. The network, represented by a graph, was reduced by “combining” links in series and parallel.

Gartner proposed a dynamic programming technique to address the problem that was published as the Generalized Combination Method and validated by field testing (Gartner N., 1971; 1973; 1975).

TRANSYT was also based on the relationship of delay and offset, which has been introduced in Section 2.4.1. It is one of the first optimization packages to model platoon dispersion. In the beginning, TRANSYT optimized network offsets by using a heuristic algorithm called “Hill-climbing algorithm”. Later, other heuristic algorithms, such as the Shotgun algorithm, the Simulated

Annealing algorithm, the Genetic algorithm were applied to escape local optima. SIGOP is another software package that searches for the optimal offset through Monte Carlo simulation. Some other software packages in this branch include SYNCHRO, CORSIM, etc. which were introduced in Chapter 2.

6.2 Data preparation

The cyclic traffic flow profile and the cyclic delay profile are the input data of the method for computing optimal offsets (Robertson, D. I., 1974). To make it easy to explicate the method, the network in Figure 6-2 is employed. Detectors L_{AB} and L_{BA} record traffic counts in small time-bins of each direction. The traffic counts then are stored as the matrix of cycle length by cycle number $(\mathrm{M}_{I\times J})$. In other words, the number of column (J) equals the value of cycle length divided by the bin length (i.e. the record frequency) and the number of row (I) equals the number of cycles during the reordering time. So the entry m_{ij} represents the traffic count of the jth bin in the ith cycle. The bin length can be set as 2s or more. The average traffic count of each bin composes the cyclic flow profile $(\vec{q})$, which can be written as:

$$\vec{q} = [q_1, q_2, \cdots, q_i, \cdots, q_J] \tag{6.2}$$

Where:

q_i is the traffic flow of the ith bin, (vehicle/bin);

J is the number of total bins of one cycle.

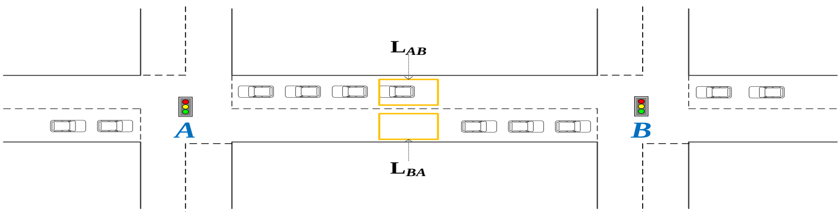


Figure 6-2 Road configuration

For example, the common cycle length of the network in Figure 6-2 was set as 40s, and the bin length was 2s. The traffic demands of east-west directions were 600 vehicles/h. The record time was 15 minutes (900s), so there were 22 bin-by-bin traffic counts. This scenario was run in SUMO. The cyclic flow profile of the link between intersection A and B was shown in Figure 6-3.

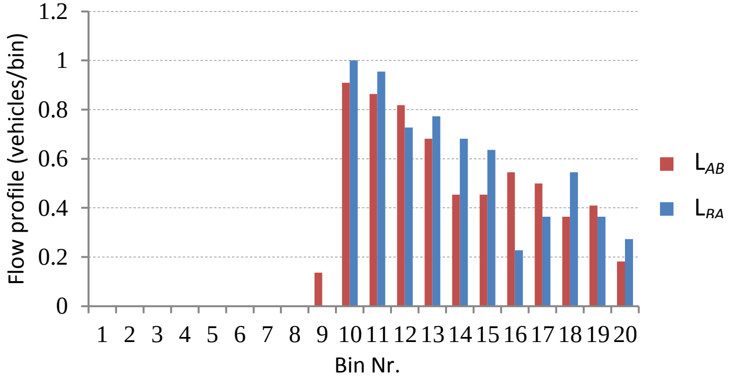


Figure 6-3 Cyclic flow profile of two detectors

6.3 A method for optimal offsets

The measure of the effectiveness of the offset at two adjacent intersections is the total delay per cycle. The cyclic flow profiles of two parallel paths between intersection A and B (q_{AB}, q_{BA}) have been prepared by the previous section, see Figure 6-3.

The vehicles in each bin correspond to a delay time because of the phase configuration. Obviously, a delay time can be assigned to each bin:

$$\vec{d} = [d_1, d_2, \cdots, d_i, \cdots, d_J] \tag{6.3}$$

So the total delay is

$$D = \vec{q} \cdot \vec{d} = q_1 \cdot d_1 + q_2 \cdot d_2 + \cdots + q_J \cdot d_J. \tag{6.4}$$

Now the question is how to calculate the delay time of each bin. The cycle length, the green splits and the position of the detectors have to been given before calculating the delay of each bin. Take the detector loop on westbound of intersection B as an example, the distance (D) between the detector and stop line of intersection is 80m, the free flow travel speed (v) is 13.8 m/s

(50km/h). The detector can be located typically 50m-100m ahead of the intersection. If placing the detector too far away from the downstream intersection, the traffic dispersion affects the accuracy of flow profiles; if placing detector too near to the downstream intersection, vehicles may queue over the detectors when the light is red. The travel time (t_W) from detector to intersection is

$$t_W = D/v = 80/13.8 \approx 6(s). \tag{6.5}$$

Supposing the offsets of both intersections are 0s. The green time is t_g seconds, the yellow time is t_y seconds, and the red time is t_r seconds. The green time start once the traffic light start. Therefore, between t_W and t_g, the delay of each bin is 0s. The delay of the first bin of t_y is also considered as 0s. The delay of other time of the cycle is an arithmetic progression (AP) or arithmetic sequence, and the initial term is $t_y - t_b + t_r$. Here: t_b is the bin length. The common difference of successive members is t_b. The number of bins with 0s delay comprise two parts, N_1 and N_3, which are:

$$N_1 = ceil\left(\frac{(t_g - t_W)}{t_b}\right) + 1$$
$$N_3 = \frac{t_W}{t_b} \tag{6.6}$$

The number of bins with successive decreasing delay, N_2, is:

$$N_2 = floor\left(\frac{(c-t_g)}{t_b}\right) - 1. \tag{6.7}$$

In the example of Figure 6-4, the cycle time c is 50s, the green time t_g is 24s (shown as the bar filled in green), the yellow time t_y is 4s (shown as the bar filled in yellow), the red time t_r is 22s (shown as the bar filled in red), and the bin length t_b is 2s. The delay of each bin in one cycle is determined by the phase, shown as the number on the green bar, yellow bar, and red bar, i.e.

$$\overrightarrow{d_{AB}} = [0,0,0,0,0,0,0,0,0,0,24,22,20,18,16,14,12,10,8,6,4,2,0,0,0]$$

$$\overrightarrow{d_{BA}} = [0,0,0,0,0,0,0,24,22,20,18,16,14,12,10,8,6,4,2,0,0,0,0,0,0].$$

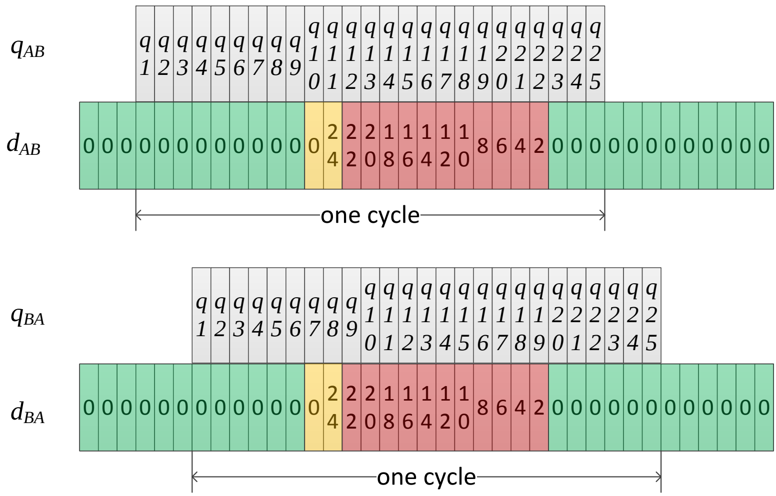


Figure 6-4 Cyclic flow and cyclic delay

So when the offset is 0s, the total delay for link from intersection A to B is

$$D_{AB} = \overrightarrow{q_{AB}} \cdot \overrightarrow{d_{AB}}. \tag{6.8}$$

The total delay for link from intersection B to A is

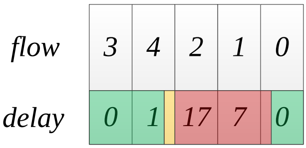
$$D_{BA} = \overrightarrow{q_{BA}} \cdot \overrightarrow{d_{BA}}. \tag{6.9}$$

The total delay for both links is

$$D = D_{AB} + D_{BA}. \tag{6.10}$$

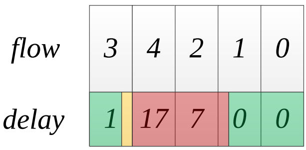
It might be argued that the delay computed in this way is not accurate. That is possible; however, what should be cared about is not the precious value of delay time, but the correct order of delay time corresponding to the offset. In other words, if the delay reflects the relationship with offset, this delay time is good enough here.

To explain conveniently, it is supposed that there are five bins per cycle. When the offset is 0s, the cyclic flow profile of coordinated links is $\overrightarrow{q_{AB}} = [3,4,2,1,0]$ and $\overrightarrow{q_{BA}} = [1,2,4,1,1]$, and the delay per bin of eastbound and westbound are $\overrightarrow{d_{AB}} = [0,1,17,7,0]$ and $\overrightarrow{d_{BA}} = [0,2,20,10,0]$. Also the color of bins means the color of traffic light. When the offset of intersection A is 0 and the offset of intersection *B* is 0, i.e. φ = [0,0] (the unit is bin), the delay of vehicles on the link from intersection *A* to intersection *B* is:



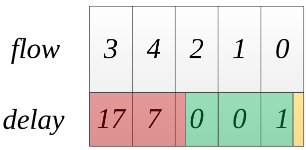
$$D_{AB} = \overrightarrow{q_{AB}} \cdot \overrightarrow{d_{AB}} = 0 + 4 + 34 + 7 + 0 = 45s.$$

In the diagram, just move delay bins left one bin. Then the offset of intersection *A* is 0 and the offset of intersection *B* is 1, i.e. φ = [1,0] (the unit is bin). The delay of vehicles on the link from intersection *A* to intersection *B* is:



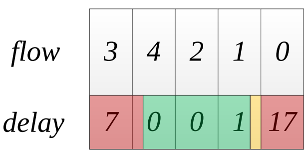
$$D_{AB} = \overrightarrow{q_{AB}} \cdot \overrightarrow{d_{AB}} = 3 + 68 + 14 + 0 + 0 = 85s.$$

When moving the delay bins left one bin again, the offset of intersection *A* is 0, the offset of intersection *B* is 2, i.e. φ = [2,0] (the unit is bin). Then the delay of vehicles on the link from intersection *A* to intersection *B* is:



$$D_{AB} = \overrightarrow{q_{AB}} \cdot \overrightarrow{d_{AB}} = 51 + 28 + 0 + 0 + 0 = 79s.$$

When the offset of intersection *A* is 0, the offset of intersection *B* is 3, i.e. φ = [3,0] (the unit is bin), the delay of vehicles on the link from intersection *A* to intersection *B* is:



$$D_{AB} = \overrightarrow{q_{AB}} \cdot \overrightarrow{d_{AB}} = 21 + 0 + 0 + 1 + 0 = 22s.$$

When the offset of intersection A is 0, the offset of intersection B is 4, i.e. $\varphi = [4,0]$ (the unit is bin), the delay of vehicles on the link from intersection A to intersection B is:

flow	*3*	*4*	*2*	*1*	*0*
delay	*0*	*0*	*1*	*17*	*7*

$D_{AB} = \overrightarrow{q_{AB}} \cdot \overrightarrow{d_{AB}} = 0 + 0 + 2 + 17 + 0 = 19s.$

Now the total delay per cycle for all possible offsets has been analyzed. From these results, it can see that if the coordination is only for eastbound direction (from intersection A to intersection B), the optimal offset is $\varphi = [4,0]$ (the unit is bin), since it has the minimal delay time. The total delay of the opposite direction (from intersection B to intersection A) for all possible offsets can be calculated by this method too. By the supposing $\overrightarrow{q_{BA}}$ and $\overrightarrow{d_{BA}}$, the result is 94, 82, 42, 32, and 38. Namely, the optimal offset if only coordinate westbound direction is $\varphi = [0,3]$ (the unit is bin).

What is worth noticing is that if the offset of one intersection is φ_1 (s), the equivalent offset expressed by its adjacent intersection is $c - \varphi_1$ (s), where c is cycle time. For example, the $\varphi = [1,0]$ (the unit is bin) of eastbound direction is equivalent to the $\varphi = [0,4]$ (the unit is bin) of westbound direction. So if the delay of both directions is requested to be minimal after coordination (offset adjustment), supposing the offset of intersection B is fixed which is 0 (the unit is bin), the total delay will be calculated as follow:

$$\begin{gathered} D(\varphi = [0,0]) = 45 + 94 = 139\text{s} \\ D(\varphi = [1,0]) = 85 + 38 = 123\text{s} \\ D(\varphi = [2,0]) = 79 + 32 = 111\text{s} \\ D(\varphi = [3,0]) = 22 + 42 = 64\text{s} \\ D(\varphi = [4,0]) = 19 + 82 = 101\text{s} \end{gathered} \tag{6.11}$$

So the optimal offset is $\varphi = [3,0]$ or $\varphi = [0,2]$, the unit is bin. The computation can be shown in Figure 6-5.

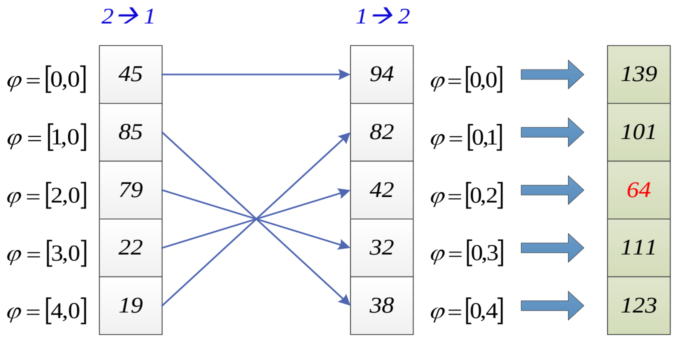


Figure 6-5 Delay of different offsets

The above computation can be thought as two wheels, the numbers on the outside wheel are the traffic flow per bin and on the inside wheel are the delay per bin as shown in Figure 6-6. The sum of multiplication of the corresponding numbers is the total delay. The objective is to find the best combination that has the minimal total delay.

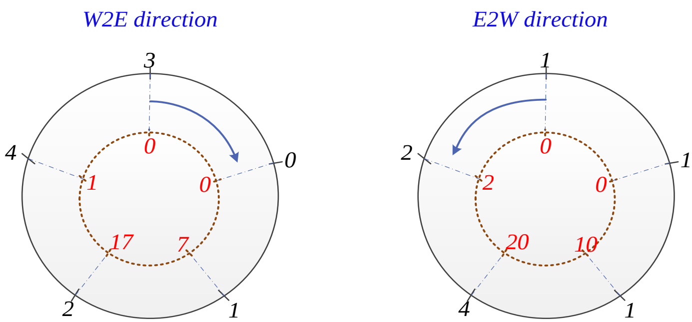


Figure 6-6 Abstract drawing of the offset calculation

6.4 Case test

The network in Figure 6-2 was used. It is possible to enumerate the MoEs (average delay per vehicle, fuel consumption, and PMx emissions) of all possible offsets. The offset was set as a variable from 0s to (cycle-1) s with 2s increments. The traffic demand was given in Table 6-1, for ten different scenarios. The effective green time for each phase of each scenario was optimized by Synchro (David Hush and John Albeck, 2006).

Table 6-1 Traffic demand of each scenario

Scenario Number	1	2	3	4	5	6	7	8	9	10
Traffic Demand of EW (veh/h)	400	600	351	549	757	753	337	500	600	700
Traffic Demand of 1 NS (veh/h)	200	200	129	422	210	523	354	300	300	300
Traffic Demand of 2 NS (veh/h)	100	200	85	619	67	319	115	200	200	200

The MoEs' tendency with the offsets of scenario 1 was shown in Figure 6-7. In the figure, the red point means the optimal offset. The offset calculated by the proposed method was 27s, which created the optimal delay time and PMx emissions. Although it did not create the optimal fuel consumption, the fuel consumption of 27s offset was only 0.054% more than the optimal fuel consumption. .

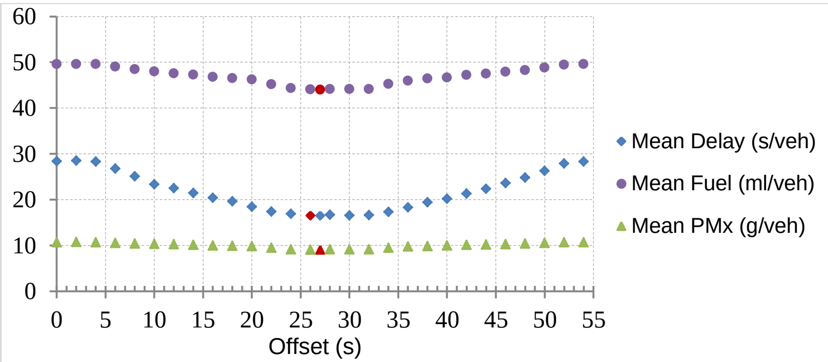
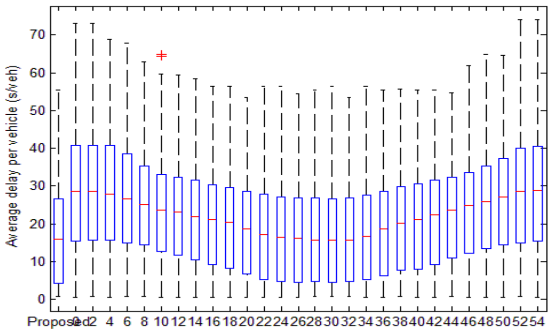


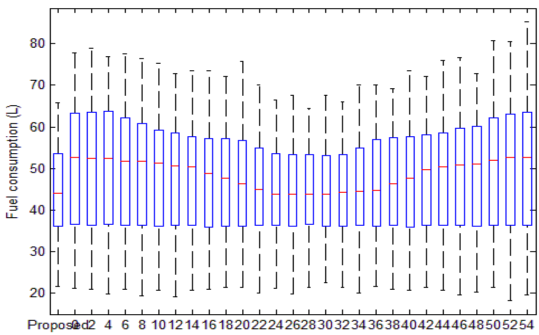
Figure 6-7 Measures of effectiveness' tendency with the offsets

It is also known that the optimal offset of different MoEs do not occur at the same offset but are close to each other. In some cases, they were even exactly the same; in some cases, they were not. For instance, the optimal offset of delay and PMx emissions for scenario 1 was 27s, but the optimal for the fuel consumption was 26s. The offsets that minimize delay, fuel consumption, and carbon monoxide emission do not coincide. This result is not new, Asim J. Al-Khalili (1985) got the same conclusion.

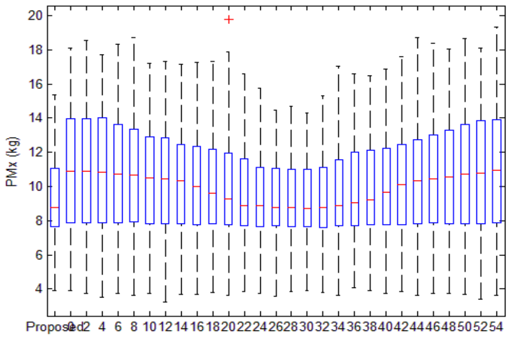
The relative changes of all MoEs are defined as the absolute difference between the value of MoE computed by the proposed method and the value by the true optimal offset, divided by the value by the true optimal offset. From the results of all ten scenarios, the relative change of mean delay was between 0 and 5.7%, of mean fuel consumption was between 0 and 3%, and of the mean PMx emissions were between 0 and 4.5%. In other words, the largest (worst) increment of delay (scenario 6) had 1.7s extra delay for each vehicle on average, of fuel consumption (scenario 6) had 1.5ml extra fuel consumption for each vehicle on average, and of PMx emissions (scenario 6) had 0.5g extra PMx for each vehicle on average. Therefore, it can be concluded that the effect of the proposed method is pretty good. The boxplots of three MoEs with offsets of scenario 1 were shown in Figure 6-8. The average delay per vehicle at the offset computed by the proposed method performed well at other nine scenarios too.



(*a*)



(*b*)



(c)

Figure 6-8 Boxplot of the relationship between delay, fuel consumption, PMx emissions and offsets of scenario 1

6.5 Summary

In this chapter, the calculation methods of micro-timing parameters including effective green time and offset were discussed. In section 6.1, the existing methods for offset optimization were reviewed at first. The effective green time of the phases is in proportion to the corresponding ratios of flow to saturation flow. In Section 6.2 and 6.3, the offset optimization method based on the cyclic flow and cyclic delay was introduced. A case with varied traffic demands was used to evaluate the effectiveness of the proposed method in Section 6.4.

At this point, the complete macro control strategy and the micro-parameter estimation have been presented.

Chapter 7
Simulation experiments

Some simulation studies were conducted to evaluate the performance of the proposed strategies. The simulations were run in SUMO. The strategies were programmed in Matlab. Firstly, the experimental process was designed. Secondly, a hypothetic case with 64 intersections was simulated and analyzed. Finally, two field networks located at Braunschweig were set up. The results would show the effectiveness of the method proposed in this work.

7.1 Experimental design

In the case studies, the O-D matrix of traffic demand is supposed to be constant in every period of optimization. It is also supposed that the fluctuation of traffic flow in every successive period is too small to be ignored when optimizing traffic signal timings. Therefore, the signal timing of the current period is optimized by the detected traffic volumes of the previous period.

Two types of detectors are required which were placed at 100m upstream of the stop line. The one type of detector was used for recording the traffic flow rate (vehicles per hour). Its output file was named as “e1.output.xml”. The other type of detector was used for recording the cyclic traffic flow (vehicles per time segment). Its output file was named as “e2.output.xml”.

The numerical experiment proceeds as follow. After the road net file, the route files, the detector files, and vehicle types file are prepared for SUMO, the simulation is run for half hour that is optimizing frequency defined before. After the simulation, the traffic flow rate of each lane in this period can be reported by the detectors' output file that is named as "e1.output.xml". The saturation degree of each link can be calculated by the detected traffic flow rate. Through the calculated saturation degrees and the Sorting Model of Priority Order (SMoPO) which has been introduced in Chapter three, the priority orders of every intersection can be computed. Once the priority orders of intersections are known, the subnet can be allocated based on the network partition strategy that has been introduced in Chapter four. Then the common cycle time of each subnet is computed by using the RiLSA method (RiLSA, 2010), and the green splits of each intersection are calculated through the ratios of flow to saturation flow (Evans H.K., 1950). Meanwhile, the average cyclic flow and cyclic delay of each phase of each coordinated link are calculated by the output files of the other type of detector. So the relative optimal offsets of adjacent intersections can be computed via the offset computation method that has been introduced in Chapter six. Then according to the network optimization strategy introduced in Chapter five, the absolute optimal offset of each intersection can be computed. Up to now, the signal timing plans of all intersections for the next half hour are prepared well. Upload the new signal timing plan that is named as "name.tls.add.xml" and run the simulation. The workflow for the traffic signal optimization is summarized in Figure 7-1.

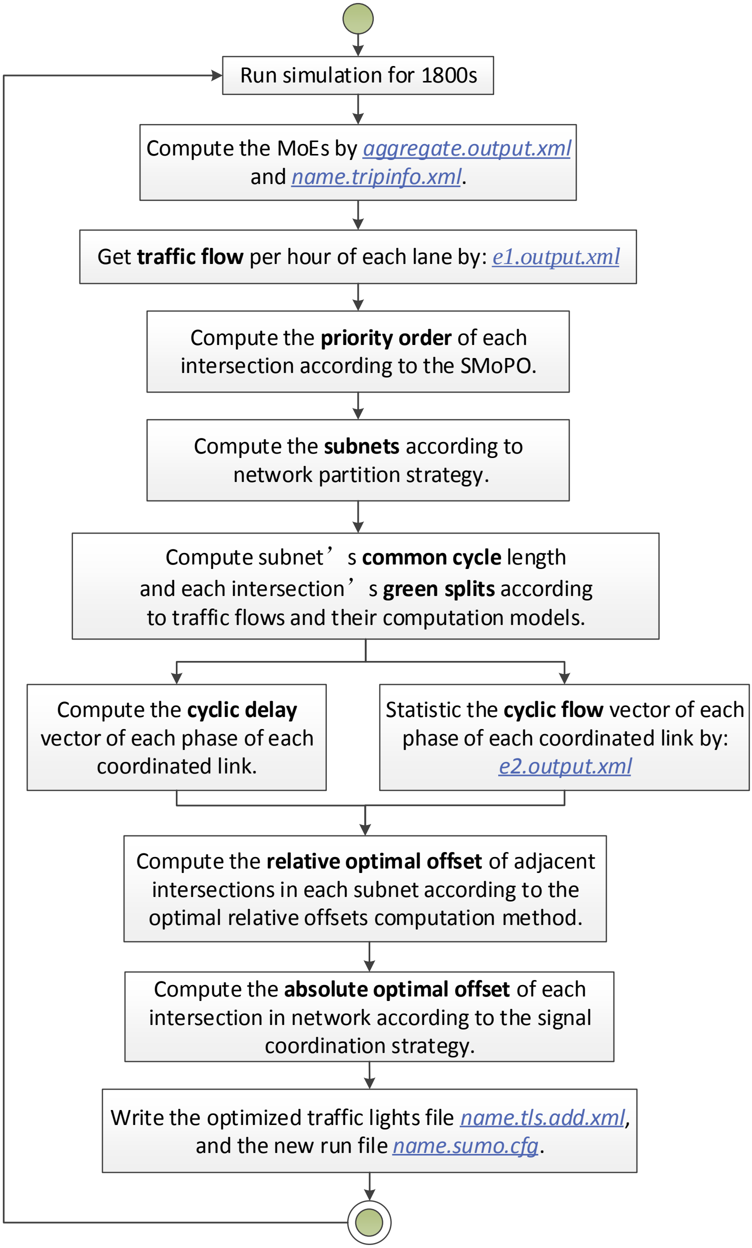


Figure 7-1 Signal optimization combined with SUMO flow chart

The algorithm of network optimization strategy that transfers the optimal relative offsets to the optimal absolute offsets is shown in Figure 7-2. In the figure, "*po*" means the priority order of junction, "φ_j" means the absolute offset of junction j, and "$\theta_{j,j-1}$" means the relative offset between junction j and junction *j-1*. The algorithm proceeds as follow: firstly, find out the junction which has the first priority, and set its absolute offset as 0; secondly, check whether its adjacent junction has the absolute offset or not. If no, compute its absolute offset. Else, find out the junction which has the next priority order. Thirdly, repeat this process until all junctions have the absolute offsets.

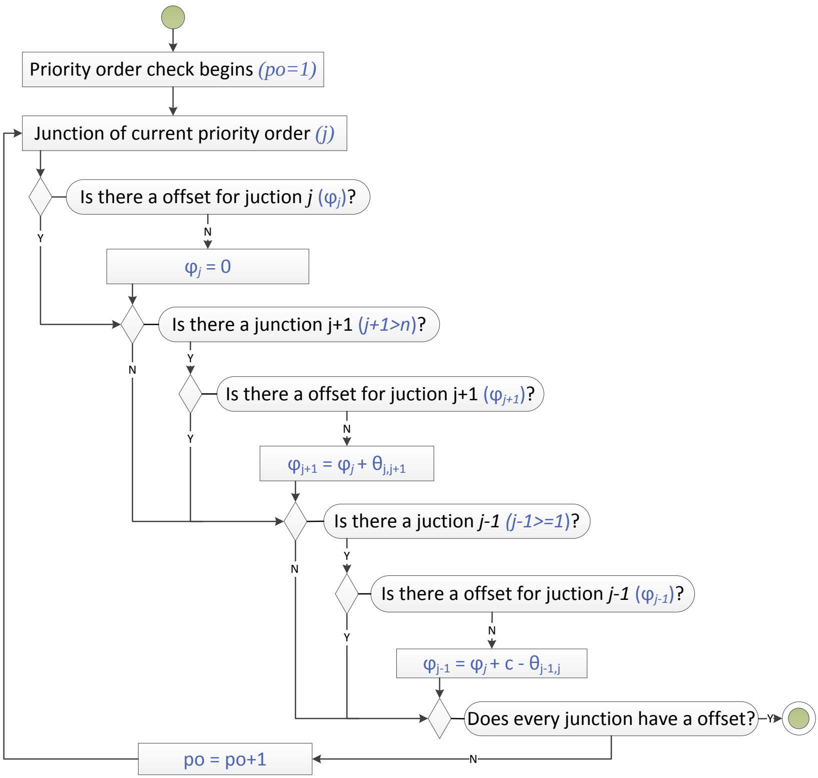


Figure 7-2 Flow chart of network optimization strategy

7.2 Speed test for strategies

Since the computation speed of the optimization strategy is the premise of real-time execution, the speeds of the strategies will be tested in this section. The strategies include priority order's computation, subnet partition, and network signal coordination. Also, because the strategies are designed for any size of network, the speed tests are used to evaluate the feasibility of the proposed strategies in different scaled network.

The trial nets are n-by-n grid nets, which mean the networks contain n^2 intersections. The computer processor is AMD II X4 840, 3.20 GHz. Because of the ordinary performance of the computer, the largest net was designed to be 60-by-60, consisting of 3600 intersections. Berlin has about 2100 intersections, as a result, it can verify the strategies' feasibility for the city in scale like Berlin. The strategies' speeds were tested from 3-by-3 grid net to 60-by-60 grid net with the increment of 3 intersections on every row and column. After experiments, the relationship between the computing speed and the size of network can be obtained.

To eliminate statistical fluctuations, 50 cases with random inputs were created for each network.

7.2.1 Speed of priority order model

A model named the Sorting Model of Priority Order (SMoPO) was described in Chapter 3, by which the optimal priority orders for intersections in the network can be computed. The input data of SMoPO is the topology of intersections and the saturation degree of every link. Here the network is a grid net with the same link length. The links' saturation degrees were randomly generated which obeys uniform distribution in the interval of [0.1, 0.9]. The plot of the relationship between the consumed time and the size of the net for all cases was shown in Figure 7-3. The blue points in the figure represent the computation time of priority order. The net size was represented by the amount of intersections in the net, shown as the horizontal coordinates. There were 50 points at each network scale, but they were too close to be distinguished. The red lines were the fitted curves for the computation time, which were fitted by the third-degree polynomial. The coefficients of determination (R^2) were about 99%. The minimal computation time was 0.0002s for the network with nine intersections, and the maximal computation time was 94.86s for the network with 3600 intersections. Therefore, it can be concluded that the speed of priority order's computation is stable, and fast to realize the real-time optimization.

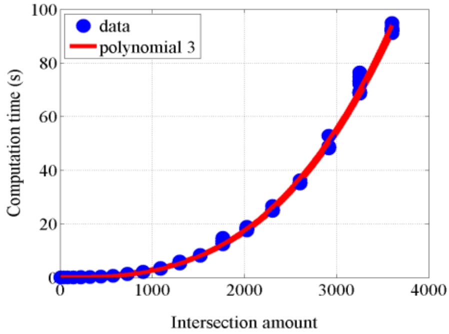


Figure 7-3 Relationship between the computation time of priority orders and the net size

7.2.2 Speed of partition strategy

The network partition strategy was described in Chapter 4, by which a network can be partitioned into some smaller subnets. The input data of this strategy is the intersection's priority order that has been computed in Section 7.2.1. The plot of the relationship between the computation time and the net size was shown in Figure 7-4. The blue points mean the computation time of network partition of each case, and the red lines were the fitted curves. There were also 50 points at each network scale that is represented by intersection amount in horizontal coordinate. Although the computation time of network partition fluctuated more than the time of priority order, the absolute time was quite small. It can be seen in the figure that the largest computation time was only 1.08s. The computation time

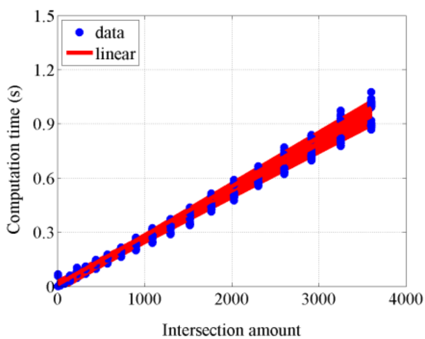


Figure 7-4 Relationship between the computation time of network partition strategy and the net size

increased linearly with the network scale, and the coefficients of determination (R^2) were about 98%. So it can be concluded that the speed of the proposed strategy was also stable and fast enough to do real-time network partition.

7.2.3 Speed of signal coordination strategy

The network signal coordination strategy was described in Chapter 5. The input data of this strategy is the intersection's priority order and its sub-network number, which have been computed in the section 7.2.1 and 7.2.2. All cases of each-size network (from 9 intersections to 3600 intersections) were tested. The plot of the relationship between the computation time of the network signal coordination and the net size is shown in Figure 7-5. The blue points mean the computation time of coordination, and the red lines were the fitted curves. It can be seen that the computation time increased linearly with the network scale, which is represented by intersection amount in horizontal coordinate. The closed points of each network scale mean the computation time was stable. It took about 16s to coordinate all intersections in the 60-by-60 grid network. Hence, it also can be concluded that the speed of network coordination strategy was stable and fast.

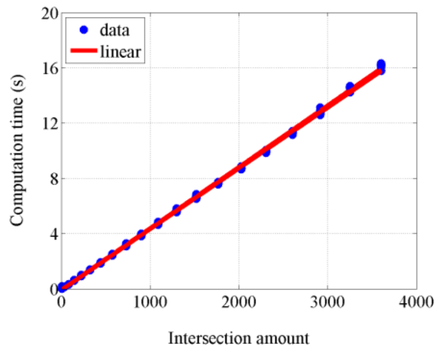


Figure 7-5 Relationship between the computation time of network coordination strategy and the net size

7.3 Hypothetical case

In this section, all strategies described in previous chapters are employed to optimize the signal timings of intersections which form an eight-by-eight grid net. There are three objectives. The first one is to evaluate the effectiveness of the proposed strategies. The comparison method is Webster's model that is most widely used in traffic signal planning in the real world. As we known that the Webster's model is for isolated control, which means there is no offset optimization. The offsets of the signal plans by the Webster's were set as 0s. Since the signal optimization tools at hand (TRANSYT-14 and Synchro Studio-7) have limitations to be used in the case studies, they couldn't be used here.

The second objective is to test the application scope of the proposed strategy. Therefore, different traffic demand levels (low, medium, and high) have been tested here.

The third objective is to measure the robustness of the proposed strategy. Fifty O-D matrixes in each demand level were created randomly, and the measures of effectiveness of these cases were simulated. Twenty of them were used to draw conclusions. The other thirty cases were used to verify the conclusions, see section 7.3.2 for more details. The amount of sample space is one of issues in the field of the sensitivity analysis. The more sample cases simply give better statistics and decrease the probability of surprises.

7.3.1 Network and phase configuration

The trial network is the 8-by-8 square grid network consisting of 64 intersections. The general layout of the network is shown in Figure 7-6, where the origins and destinations were labeled in blue, and the intersections were labeled in red. Each link had one lane, and its length was 400m. The detectors were placed at 100m upstream of the intersection stop lines. This distance could allow a good estimation of the cyclic traffic flow at the downstream stop line because the platoon will not disperse significantly over such a short distance, and the queue will not spill out frequently. The phase configuration is the same to every intersection. The first phase is for vehicles on eastern and western approaches, and the second phase is for vehicles on northern and southern approaches. The minimal common cycle length for the network was 40s and the maximal was 120s. The yellow time and the lost time was 4s per phase. The common cycle length of subnets was determined by the method in RiLSA (RiLSA, 2010), by which the optimal cycle time of the critical intersection in the subnet was defined as the common cycle time.

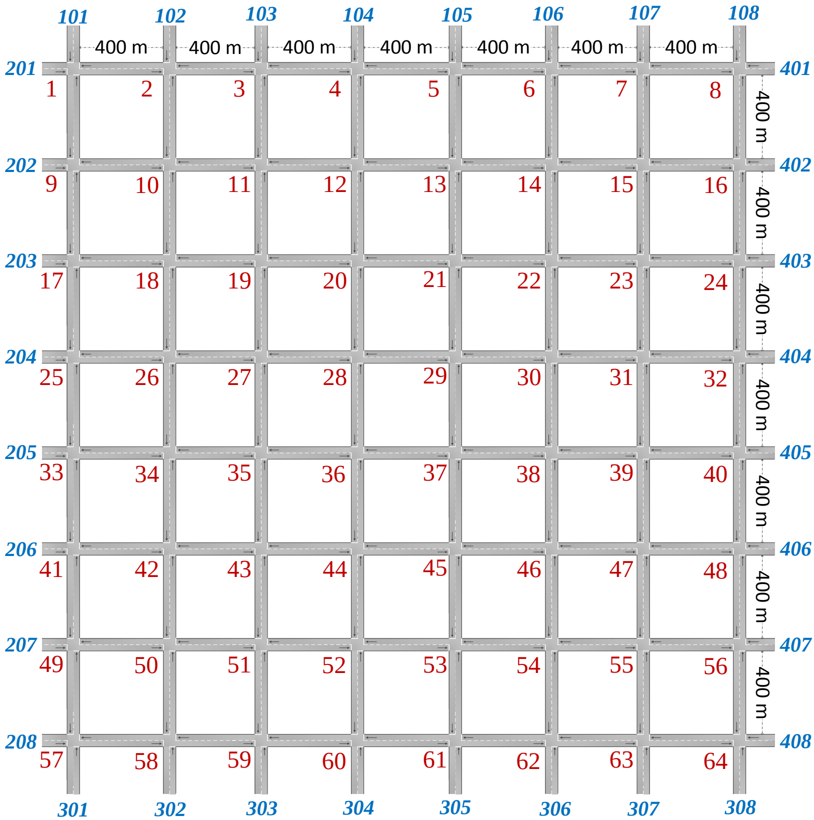


Figure 7-6 Layout of trial network

7.3.2 Result

• ***Low traffic demand***

Twenty cases with random O-D matrixes were created. The elements of matrixes were drawn from a uniform distribution in the interval [200, 400] (vehicles/hour). The mean delay of each case optimized by the proposed strategy and the Webster's model was shown in Figure 7-7.

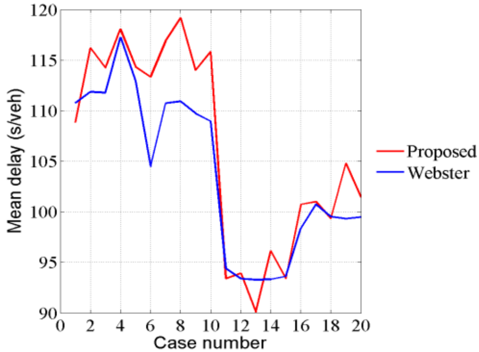


Figure 7-7 Mean delay time in low traffic demand

It can be seen that the delay by the proposed strategy was close to or a little bit worse than the one of the Webster's model. Its relative change compared with the delay by the Webster's model was shown as the blue dot-dash line in Figure 7-8. The relative change equals the absolute difference between the delay of the proposed strategy and the delay of the Webster's model divided by the delay of the Webster's model. The relative change in fuel consumption and PMx emissions were computed in the same way. It was shown that the mean delay by the proposed model underperformed the Webster's model by 2%. It meant that the proposed strategy was not always effective with the delay as the measure of effectiveness (MOE) in low traffic demand.

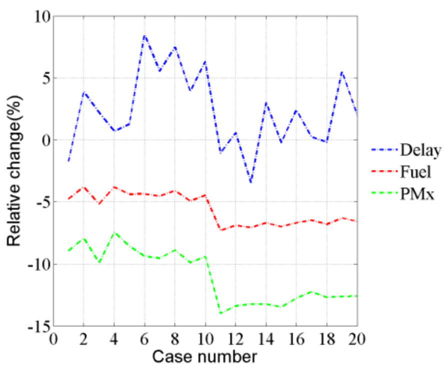


Figure 7-8 Relative changes of proposed strategy compared with Webster's model in low traffic demand

Regarding fuel consumption as the measure of effectiveness (MOE), the proposed strategy is always better than the Webster's model as can be seen in Figure 7-9. Its relative change compared with the fuel consumption by the Webster's model was shown as the red dot-dash line in Figure 7-8. It was shown that the mean fuel consumption by the proposed strategy outperformed the Webster's model by about 5%, which means that the proposed strategy was effective when taking the fuel consumption as MOE in low traffic demand.

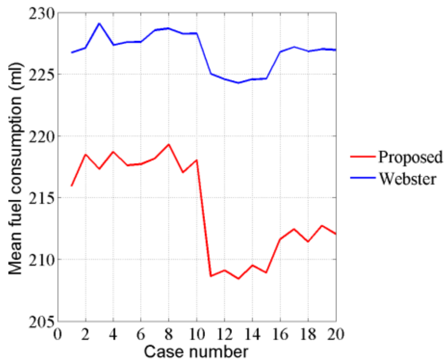


Figure 7-9 Mean fuel consumption in low traffic demand

If take PMx emissions as the measure of effectiveness (MOE), then the PMx emissions of each case optimized by proposed strategy and the Webster's model were shown in Figure 7-10. It can be seen that the PMx emissions by the proposed strategy were also smaller (better) than the Webster's model. Its relative change was shown as the green dot-dash line in Figure 7-8. It was shown that the PMx emissions by the proposed strategy outperformed the Webster's model by about 10%, which indicated the proposed strategy was effective when taking PMx emissions as MOE in low traffic demand.

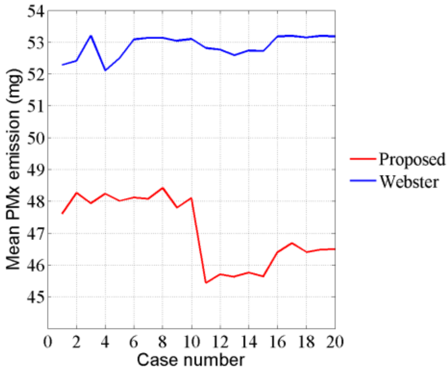


Figure 7-10 Mean PMx emission in low traffic demand

The reason why the proposed strategy was worse than the Webster's model in the delay time, but better in the fuel consumption and PMx emissions could be that the stop times of vehicles were decreased through the signal coordination. The effect on delay time from the signal coordination was not obvious since the traffic flow was small, but the effect on stops was still strong. Moreover, the fuel consumption and PMx emissions were caused not only by the travel time, but also travel conditions like smooth driving or the number of stops.

• *Medium traffic demand*

Twenty cases with random O-D matrixes were created, whose elements obeyed uniform distribution in the interval of (400, 800) (vehicles/hour). The mean delay of each case optimized by the proposed strategy and the Webster's model was shown in Figure 7-11. It can be seen that the delay by the proposed strategy outperformed the Webster's model in all cases. Its relative change compared with the delay by the Webster's model was shown as the blue dot-dash line in Figure 7-12. Clearly, the proposed strategy was effective and decreased mean delay by 2% at least and 18% at most.

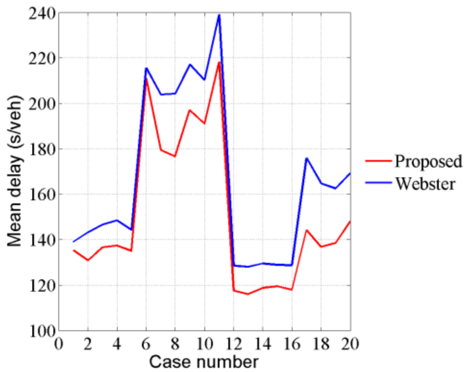


Figure 7-11 Mean delay time in medium traffic demand

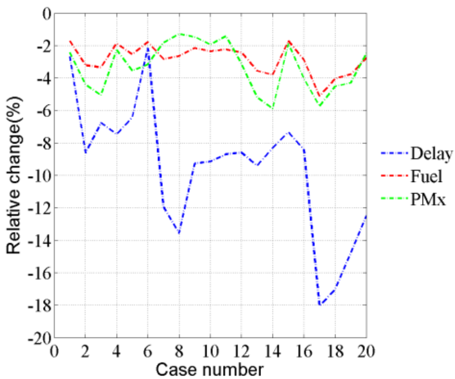


Figure 7-12 Relative change of proposed strategy compared with Webster's model in medium traffic demand

If take the fuel consumption as the measure of effectiveness (MOE), then the fuel consumption of each case optimized by the proposed strategy and the Webster's model was shown in Figure 7-13. It can be seen that the fuel consumption by the proposed strategy was smaller than the Webster's model in all cases. Its relative change compared with the fuel consumption by the Webster's model was shown as the red dot-dash line in Figure 7-12. It was shown that the mean fuel by proposed strategy was smaller than the Webster's model by about 3%, which indicated the proposed strategy was effective when taking the fuel consumption as MOE in medium traffic demand.

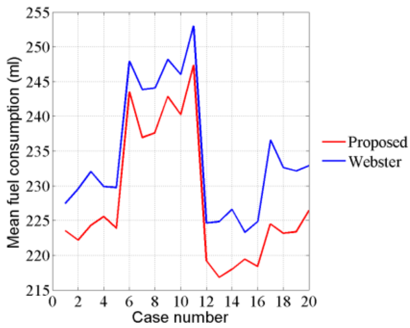


Figure 7-13 Mean fuel consumption in medium traffic demand

If take PMx emissions as the measure of effectiveness (MOE), then the PMx emissions of each case optimized by the proposed strategy and the Webster's model were shown in Figure 7-14. It can be seen that the PMx emissions by the proposed strategy were smaller than the Webster's model, and in the similar trend of the fuel consumption in Figure 7-13. Its relative change compared with the PMx emissions by the Webster's model was shown as the green dot-dash line in Figure 7-12. It was shown that the proposed model decreased PMx emissions by about 4% on average, which indicated the proposed strategy was effective when taking PMx emissions as MOE in medium traffic demand.

So it can be concluded that the proposed strategy performed well when taking all these MOEs (delay time, fuel consumption, and PMx emissions) in medium traffic demand.

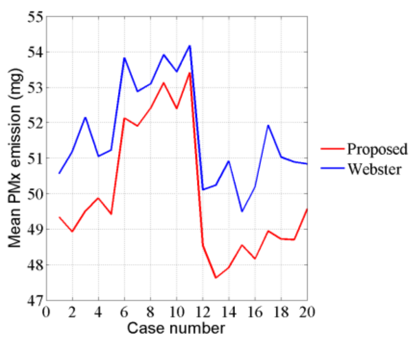


Figure 7-14 Mean PMx emission in medium traffic demand

• ***High traffic demand***

Twenty cases with random O-D matrixes were created, whose elements obeyed uniform distribution in the interval of [800, 1000] (vehicles/hour). The mean delay of each case optimized by the proposed strategy and the Webster's model was shown in Figure 7-15. It can be seen that the delay by the proposed strategy was larger than the Webster's model in all of the cases.

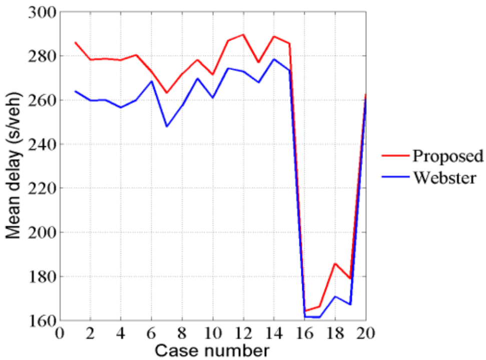


Figure 7-15 Mean delay time in high traffic demand

Its relative change compared with the delay by the Webster's model was shown as the blue dot-dash line in Figure 7-16. It was shown that the mean delay by the proposed model was increased by about 5%, which indicated the proposed strategy was invalid when taking the delay as measure of effectiveness (MOE) in high traffic demand.

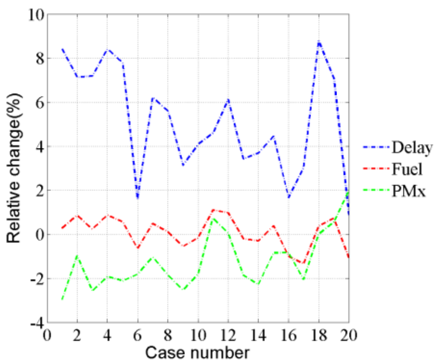


Figure 7-16 Relative change of proposed strategy compared with Webster's model in high traffic demand

If take fuel consumption as the measure of effectiveness (MOE), then the fuel consumption of each case optimized by the proposed strategy and the Webster's model was shown in Figure 7-17. It can be seen that the fuel consumption by the proposed strategy was smaller (better) than the Webster's model in almost half cases, and in other cases, it was larger (worse) than the Webster's model. Its relative change compared with the fuel consumption by the Webster's model was shown as the red dot-dash line in Figure 7-16. It was shown that the changes by two methods swayed near 0.

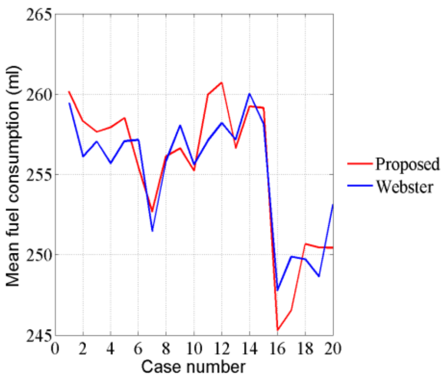


Figure 7-17 Mean fuel consumption in high traffic demand

If taken PMx emissions as the measure of effectiveness (MOE), then the PMx emissions of each case optimized by the proposed strategy and the Webster's model were shown in Figure 7-18. It can be seen that in sixteen cases, PMx emissions by the proposed strategy were smaller (better) than the Webster's model, but there were still four worse (larger) cases. Its relative change compared with the PMx emissions by the Webster's model was shown as the green dot-dash line in Figure 7-16. It was shown that the proposed model decreased PMx emissions by about 1% on average.

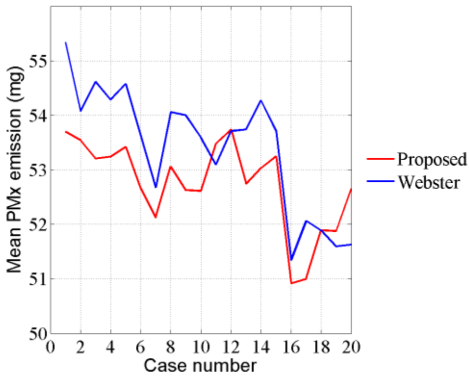


Figure 7-18 Mean PMx emission in high traffic demand

So it can be concluded that the proposed strategy was invalid in high traffic demand. This conclusion is reasonable. On the one hand, the demand has exceeded the road capacity in high traffic demand, so traffic signal has no capability to improve the traffic status. On the other hand, due to the nature of microscopic models, their calibration is not very exact in congested conditions.

- ***Robustness***

In summary, the effectiveness of the proposed strategy compared with the Webster's model in different traffic demand levels is shown in Table 7-1.

Table 7-1 Summary of the effectiveness of proposed strategy

MOE / Traffic demand	Delay	Fuel	PMx
Low	0	1	1
Medium	1	1	1
High	0	0	1

Note for the table: if the proposed strategy outperforms the Webster's model, it scores one point; else if the proposed strategy underperforms or similar to the Webster's model, it scores 0.

If the scores are seemed as the elements of the effectiveness vector ($\vec{E}$), there are three effectiveness vectors. They are $\vec{E_l} = [0,1,1]$ for low traffic demand,

$\overrightarrow{E_m} = [1,1,1]$ for medium traffic demand, and $\overrightarrow{E_h} = [0,0,0]$ for high traffic demand.

To verify the conclusions that have been get above, thirty O-D matrixes of each demand level were created randomly. Then the optimization and simulation was run for each of them. Secondly, the effectiveness vector ($\vec{E}$) of each case was resolved from the result of the simulation. Thirdly, in contrast to the Table 7-1, the demand level of each case would be found out. At last, the accuracy of judgment for the demand level could be obtained by contrasting to their real demand level. If the accuracy rate is high, it means the conclusion is reliable, and the strategy has high robustness; and vice versa.

The experiments' results showed that more than 90% cases obeyed the conclusions. The boxplot of mean delay for all of fifty cases was illustrated in Figure 7-19. It can be seen that the proposed strategy outperformed (less delay) the Webster's model only in medium traffic demand, so the effectiveness vector was $\overrightarrow{E_D} = [0,1,0]$. The effectiveness of the delay time in low, medium, and high demands in Table 7-1, the first column, was also [0,1,0].

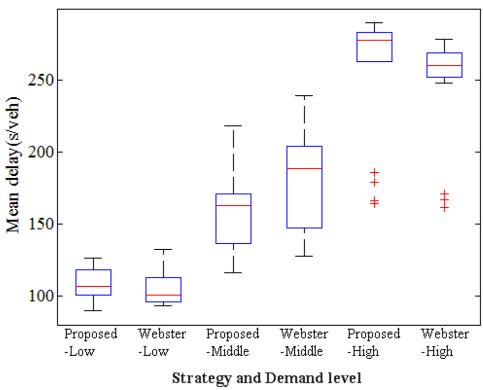


Figure 7-19 Boxplot of delay time in different traffic demands

The boxplot of mean fuel consumption for all of fifty cases was shown in Figure 7-20. It can be seen that the proposed strategy outperformed (less fuel consumption) the Webster's model in low and medium traffic demands, so the effectiveness vector was $\overrightarrow{E_F} = [1,1,0]$. The effectiveness of fuel consumption in low, medium, and high demands in Table 7-1, the second column, was also [1,1,0].

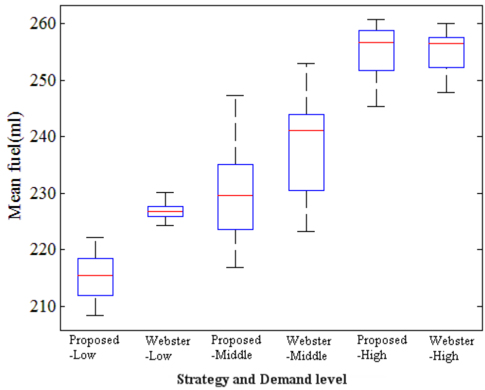


Figure 7-20 Boxplot of fuel consumption in different traffic demands

The boxplot of mean PMx emissions for all of fifty cases was shown in Figure 7-21. It can be seen that the proposed strategy outperformed (less PMx emissions) the Webster's model in all traffic demands, so the effectiveness vector was $\overrightarrow{E_P} = [1,1,1]$. The effectiveness of PMx emissions in low, medium, and high demands in Table 7-1, the third column, was also [1,1,1].

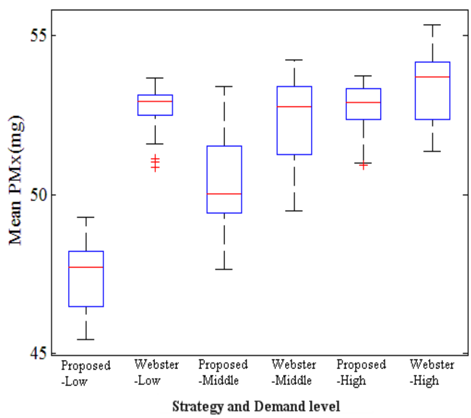


Figure 7-21 Boxplot of PMx emissions in different traffic demands

In summary, the cases showed a high robustness. However, more tests with other and/or more realistic networks are needed to demonstrate the strategy's scope and robustness further.

7.3.3 Uncertainty analysis of link length

So far, the networks were highly symmetric. To generalize the results here, networks with varied link lengths was built. The link lengths were created randomly in the range of [300, 800] (meters). The network has 64 intersections. The link has a single lane in each direction. The detector loops were placed at 100m before the stop line of downstream intersection.

The OD matrixes in low, medium, and high traffic demand were defined and created randomly as before in section 7.3.2. The common cycle length of subnets was defined as the isolated optimal cycle time of the critical intersection in the subnet. The critical intersection was the one has highest priority order in its subnet. The performance of delay time, fuel consumption, and PMx emissions by the proposed strategy and the Webster's model was shown in Figure 7-22, 7-23and 7-24.

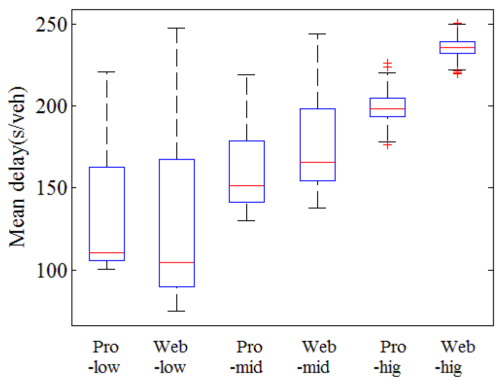


Figure 7-22 Mean delay by the proposed strategy and Webster's model in low, medium and high traffic demands

It can be seen from Figure 7-22 that, when looking at the changes in median value, the delay time by the proposed strategy was less than the Webster's model in medium and high traffic demands, but was more in low traffic demand. Compared this figure with Figure 7-19, they had the same tendency in median value in low and medium demands, which indicated the effectiveness of the proposed strategy was not affected by the link length. Although the tendency in high traffic demand was different, the effectiveness of the proposed strategy was better in this case study. When looking at the interquartile range (IQR), the delay time in lower traffic demand had more dispersion than the higher traffic demand, and the dispersion of the delay time by the Webster's model was more than the proposed strategy in low and medium traffic demands.

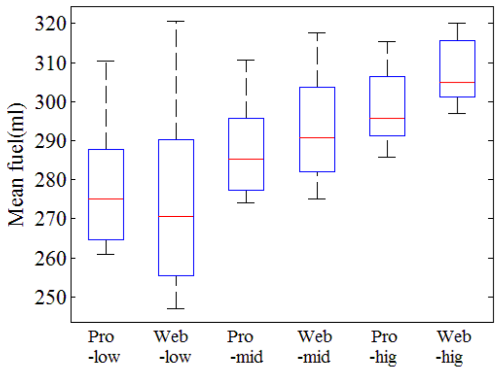


Figure 7-23 Mean fuel consumption by the proposed strategy and Webster's model in low, medium and high traffic demands

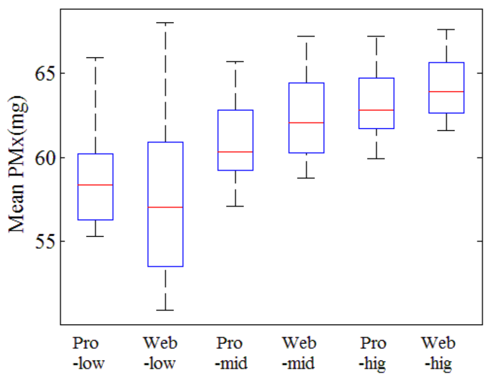


Figure 7-24 Mean PMx emissions by proposed strategy and Webster's model in low, medium and high traffic demands

It can be seen from Figure 7-23 and Figure 7-24 that the tendency of the mean fuel consumption and PMx emissions is similar with the tendency of mean delay time when looking at the changes in median value and the interquartile range (IQR). Comparing Figure 7-23 with Figure 7-20, they had the same tendency in median value in medium demand. Besides, the effectiveness of the proposed strategy in high traffic demand was better here. Comparing Figure 7-24 with Figure 7-21, they had the same tendency in median value in medium and high demands.

In summary, the results indicated the proposed strategy performed well in medium and high traffic demands in the net with varied link lengths, but worse in low traffic demand. Through the comparison of the effectiveness with the net with the same link lengths, the effects of the proposed strategy can't be affected in medium traffic demand, and the positive effect in high traffic demand. There is a negative effect in fuel consumption and PMx emissions in low traffic demand.

7.4 Braunschweig case

The final tests regard part of a real network, the network of Braunschweig City. The data of the network and route file was supplied by the Institute of Transportation Systems of the German Aerospace Center (DLR) through the Project AIM (Anwendungsplattform Intelligente Mobilität; Schnieder Lars and Lemmer Karsten, 2012, 2014; Schnieder Lars et al., 2013; Tobias Frankiewicz et al., 2011, 2012).

7.4.1 Network and phase configuration

The Braunschweig road network consists of 14016 nodes and 31316 edges and 204 signalized intersections, as shown in Figure 7-25. From this, two scenarios shown as red points and blue points in Figure 7-25 have been selected. The first one (red) is the arterial including nine intersections along with Sackring, Altstadtring, Cyriaksring and Frankfurter Strasse from the northern junction at Hildesheimer Strasse, Rudolfstrasse and Sackring, as shown in Figure 7-26. The second one (blue) is the net including seven intersections along with Rebenring, Hans-Sommer-Strasse, as shown in Figure 7-27.

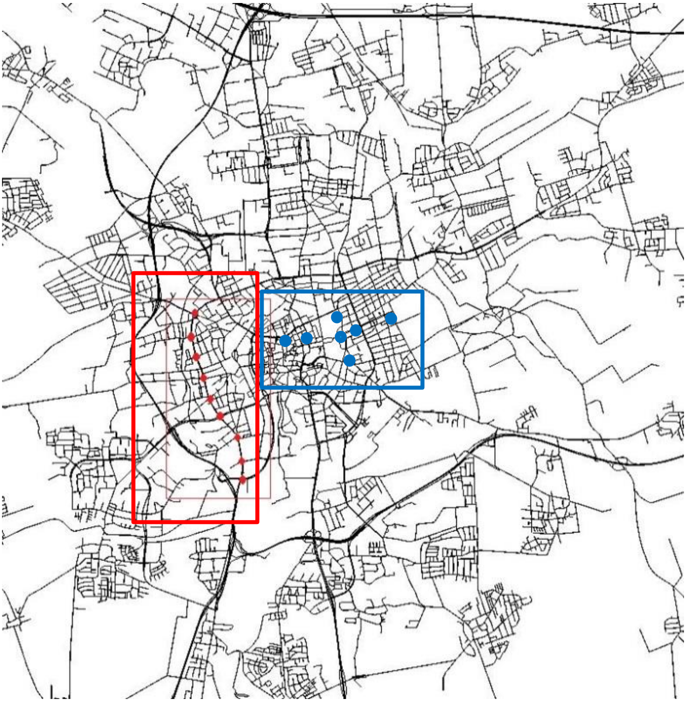


Figure 7-25 Braunschweig network

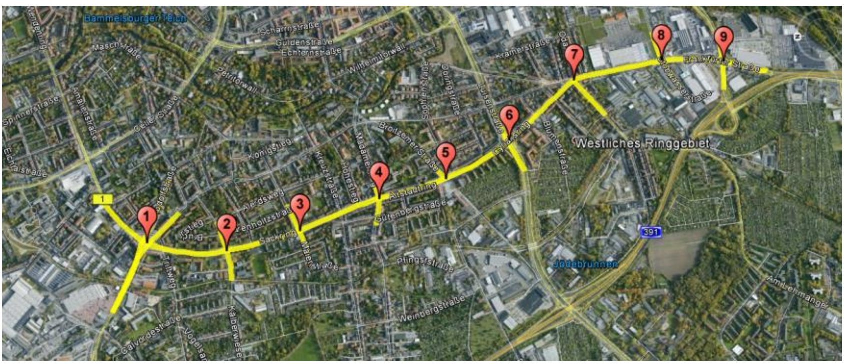
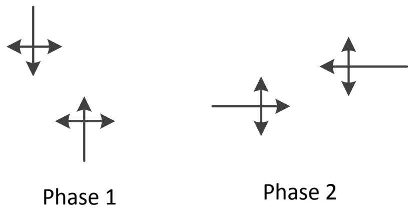


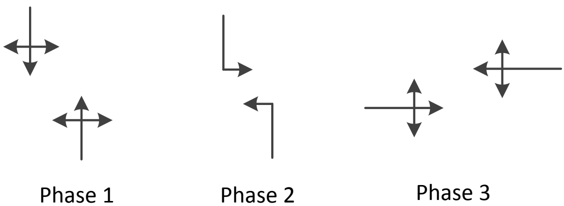
Figure 7-26 Road layout of scenario 1

Figure 7-27 Road layout of scenario 2

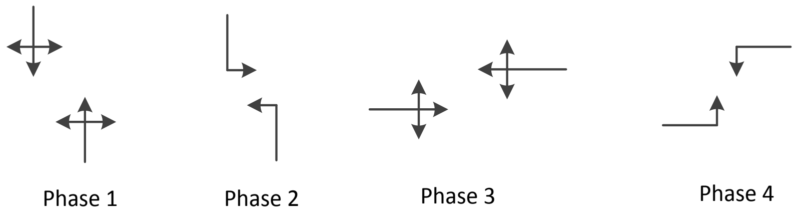
For the first scenario, the intersections 1, 5 and 8 have two phases, the intersections 2, 3 and 7 have three phases, and the intersections 4, 6 and 9 have four phases. Their phase configurations were depicted in Figure 7-28. The minimal green time of each phase was set at 6s and the lost time was set as 4s per phase. The phase configuration and the intergreen time of the second scenario are from the report of Siemens AG. The traffic flow in Tuesday, Wednesday and Thursday were same (the same route file), and differ in the other days (individual route files).



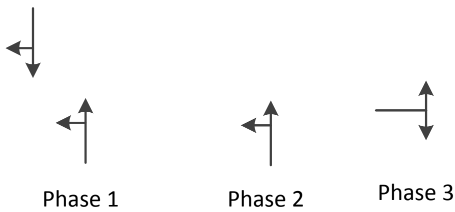
a) Phase configuration of intersection 1, 5 and 8



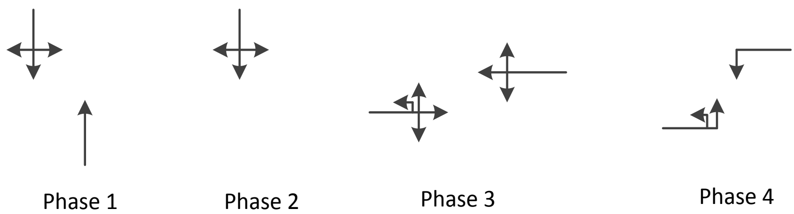
b) Phase configuration of intersection 2 and 3



c) Phase configuration of intersection 4 and 6



d) Phase configuration of intersection 7



e) Phase configuration of intersection9

Figure 7-28 Phases configuration of intersections of scenario 1

7.4.2 Result of the first scenario

The signal plans were optimized every half hour from 6:00 to 21:30. The traffic of the whole week was simulated.

At first, the intersections' priority orders were computed by the Sorting Model of Priority Order (SMoPO) in every half hour. The distribution of the priority order in each day was shown in Figure 7-29. The intersections were expressed by "I" plus its label numbers that are in Figure 7-26, and the numbers on the vertical coordinate are the priority orders. The first four priority orders were often taken by the intersection 3, 4, 5, and 6 (I3, I4, I5, I6), and rarely by intersection 7 (I7), shown in figure (a). It also can be seen that the first priority order was taken by the intersection 4 (I4) all the time except 20:30. The second and third positions of priority order were taken mainly by the intersection 5 (I5) and 6 (I6) and seldom by the intersection 3 (I3) and 4 (I4). The fourth position was the intersection 3 (I3) in most of time, and the intersection 6 (I6) and 7 (I7) rarely. According to the principle of the proposed strategies, the other lower priority orders were shown in figure (b). It can be seen that the 5th, 6th, and 7th positions of priority order were the intersection 1 (I1), 2 (I2) and 7 (I7). The last two priority orders were intersection 8 (I8) and 9 (I9). It indicated the center intersections usually have higher priority orders than the border intersections.

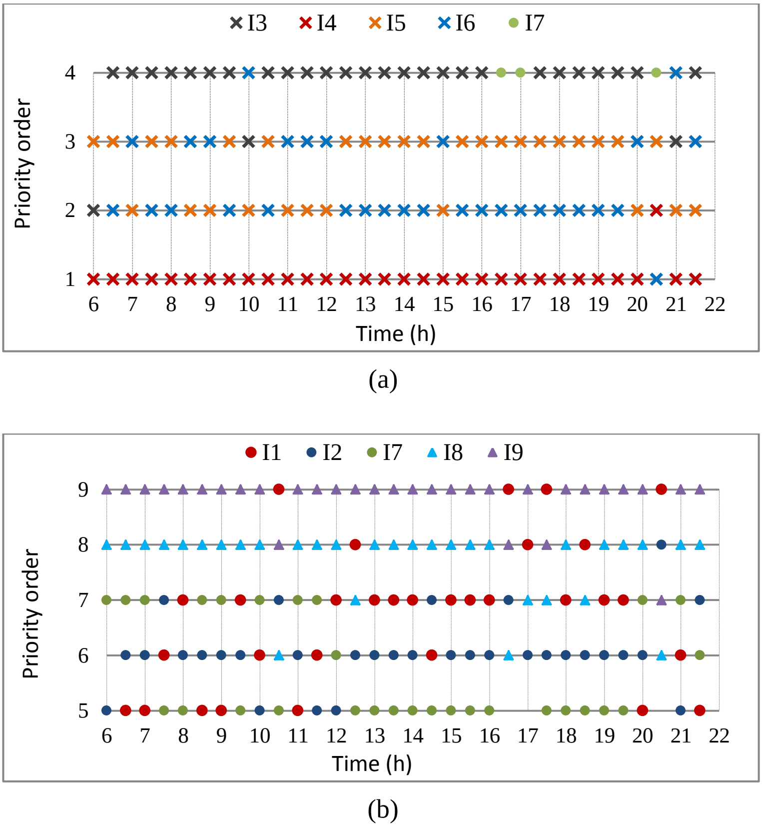


Figure 7-29 Distribution of the priority order

The common cycle time was optimized every half hour too, which was shown in Figure 7-30. This figure displayed that, the most frequent common cycle was 40s, because the traffic demand was low. In the real world, the cycle length is 85s. From the figure of Monday to Friday (labeled as Mo, Tu2Th and Fr), three traffic rush hours can be seen, which was reflected by the large cycle length. The traffic demand on the network of Sunday was lowest, only cycle time at 14:00 was higher than 40s.

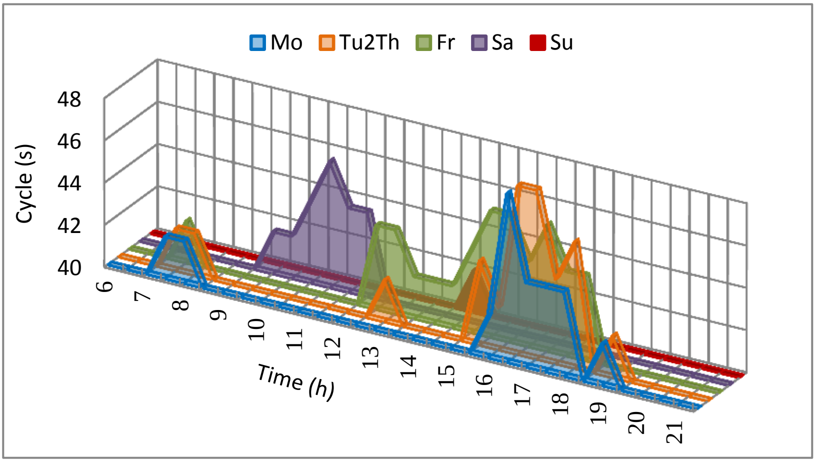


Figure 7-30 Common cycle time of scenario 1

The effectiveness of the proposed strategy was compared with two strategies. The one was the original signal plan in the SUMO net file. The other was optimized by the Webster's model (F. V. Webster, 1958), which was also restricted by the minimal cycle length of 40s and minimal green time of 6s. The offsets of the signal plans by the Webster's were set as 0s. The mean delay of all vehicles on the coordinated links of each day was shown in Figure 7-31. In the figures, the red line indicates the mean delay by the proposed strategy, the blue line indicates the Webster's model, and the black line indicated the original signal plans.

Note, that the results of the original plans have to be taken with care, they are used here for reference purposes. They are optimized for different demand, the demand used in this thesis underestimates the real demand in Braunschweig. Furthermore, the city has a policy of setting the cycle times of all the signals to 85 s, even if under some circumstances other cycle times could be better.

The Figure 7-31 showed that the mean delay by the proposed strategy was the smallest in most cases, and the mean delay of the original signal plan was the worst. So it can be said the proposed strategy was successful.

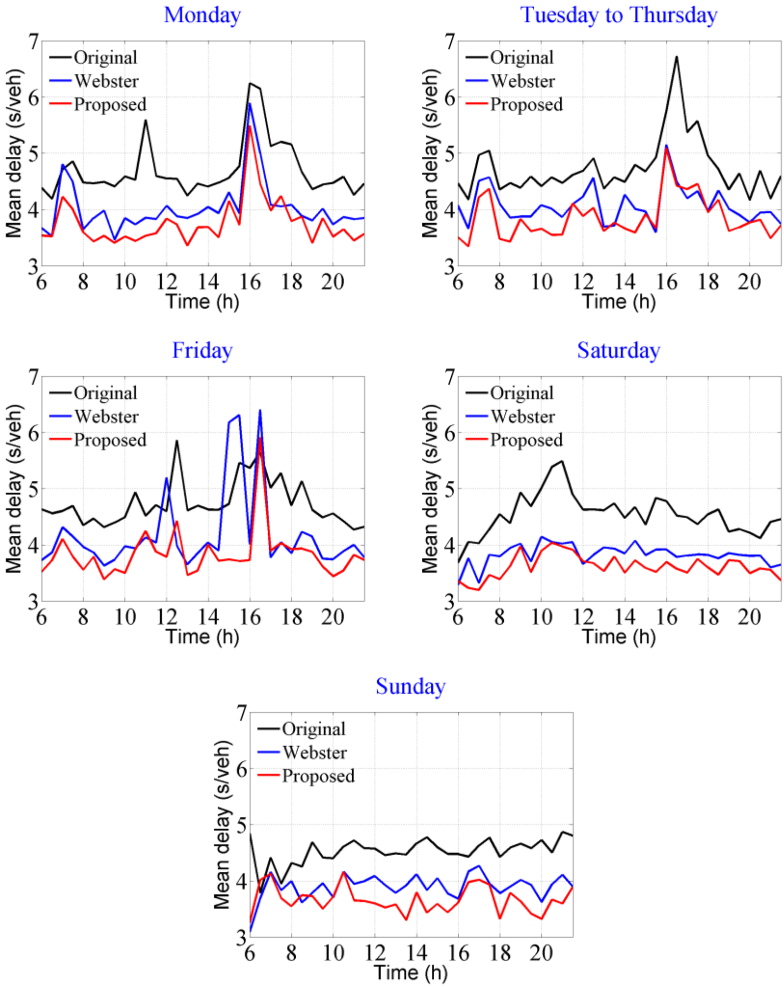
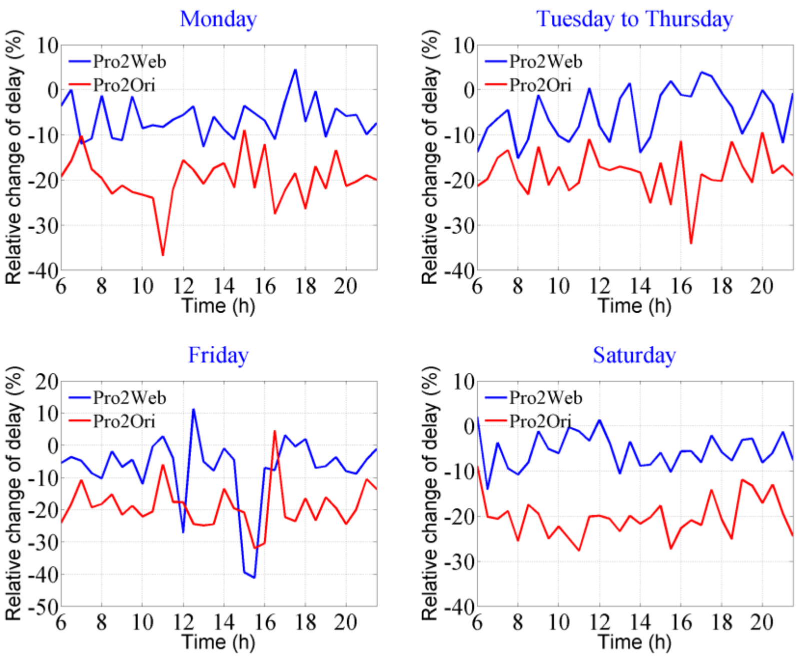


Figure 7-31 Mean delay comparison of each day of Scenario 1

The relative changes of mean delay by the three signal plan strategies were shown in Figure 7-32. They included the relative change between the proposed strategy and original plan (marked as “Pro2Ori” in figure’s legend), which was calculated by the absolute difference between the delay of the proposed strategy and original plans, and dividing by the delay of original plan. As well as, the change between the proposed strategy and the Webster’s model (marked as “Pro2Web” in figure’s legend), which was calculated by the absolute difference between the delay of the proposed strategy and the Webster’s model, and dividing by the delay of the Webster’s model. It can be seen that the mean delay by the proposed strategy was decreased by about 20% compared with the mean delay by the original plan, shown as the red line in the figure. The mean delay by the proposed strategy was decreased by about 6% compared with the Webster’s model, shown as the blue lines in the figure.



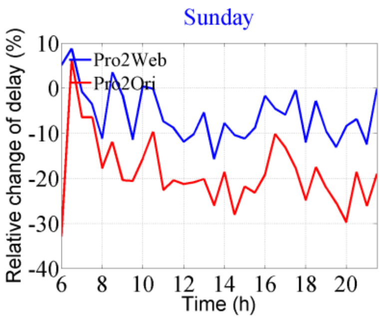


Figure 7-32 Relative change of mean delay in each day of Scenario 1

The relative improvements were time-varying. The average and maximal changes in each day were shown in Table 7-2. It was indicated that the average delay reduction by the proposed strategy taking the original plan as the reference was 18.4% at least (Tuesday to Thursday) and 20.2% at most (Saturday). The average delay reduction by the proposed strategy taking the Webster's model as the reference was 5.4% at least (Tuesday to Thursday) and 7.0% at most (Friday). The improvement to the Webster's model was much more important. And the highest improvement of mean delay by proposed strategy compared with the original plan was in Saturday, compared with the Webster's model was in Friday. The lowest improvement of mean delay by proposed strategy compared with the original plan was in Tuesday to Thursday, compared with the Webster's model was in Saturday.

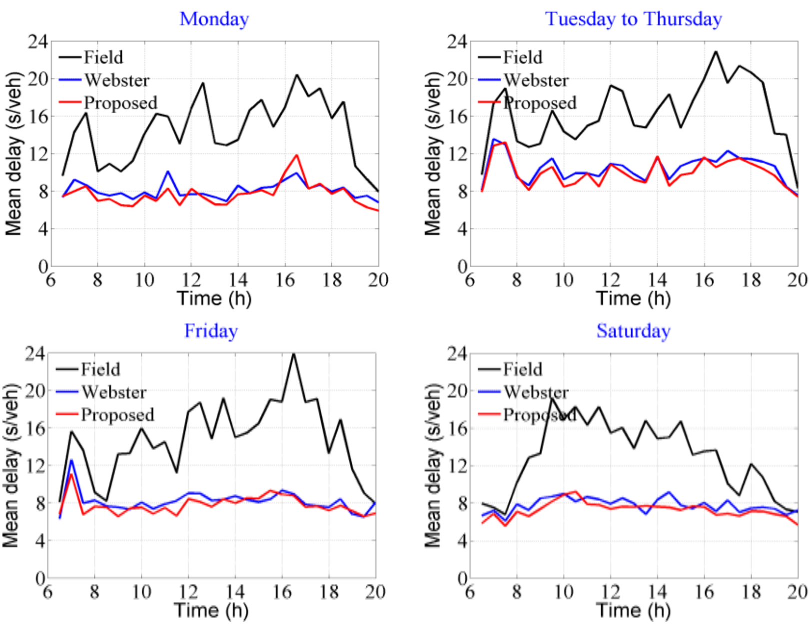
Table 7-2 Relative change of mean delay over a week of scenario 1

Strategy	Day	Mon	Tue2Thu	Fri	Sat	Sun
Proposed vs. Original	Average (%)	19.9	18.4	18.9	20.2	18.8
	Max (%)	36.8	34.2	32.0	27.7	32.8
Proposed vs. Webster's	Average (%)	6.4	5.4	7.0	5.5	5.9
	Max (%)	12.7	15.2	41.2	14.1	15.7

7.4.3 Result of the second scenario

In the second scenario, the signal plans were optimized every half hour from 6:00 to 20:00. The traffic of the whole week was simulated. The intersection that has the first priority orders was the intersection labeled Nr 47 (Figure 7-27) in almost all the time.

The effectiveness of the proposed strategy was compared with two strategies. The one was the field signal plan, and the other was optimized by the Webster's models. The mean delay of all vehicles in each day was shown in Figure 7-33. In the figures, the mean delay by the proposed strategy was shown in red line, by the Webster's model was shown in blue line, and by the field signal plans was shown in black line. It was shown that the mean delay by the proposed strategy and the Webster's model was smaller than the delay by the field signal plan, and the proposed strategy outperformed the Webster's model in most cases. So it indicated the proposed strategy was successful in this network too.



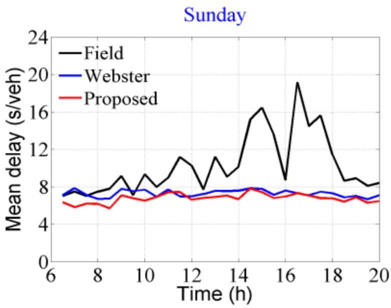
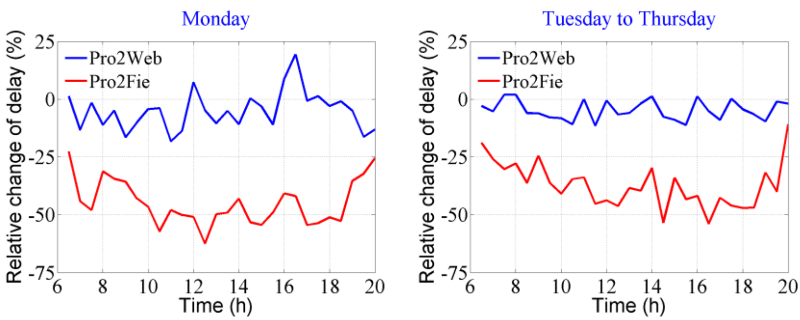


Figure 7-33 Mean delay comparison of each day of Scenario 2

The relative changes of mean delay by the three strategies were shown in Figure 7-34. They included the relative change between the proposed strategy and field plan (marked as "Pro2Fie" in figure's legend), which was calculated from the absolute difference between the delay of the proposed strategy and field plans, and dividing by the delay of field plans. As well as, the relative change between the proposed strategy and the Webster's model (marked as "Pro2Web" in figure's legend), which was calculated from the absolute difference between the delay of the proposed strategy and the Webster model, and dividing by the delay of the Webster's model. It was indicated in the figures that compared with the field plan, the mean delay by the proposed strategy was decreased by about 39% on average, which is shown by the red line in the figure. The mean delay by the proposed strategy was decreased by about 6% on average compared with the Webster model, which was shown in the blue line in the figure. Therefore, the improvement of the delay time by the proposed strategy compared to the field plan was quite large.



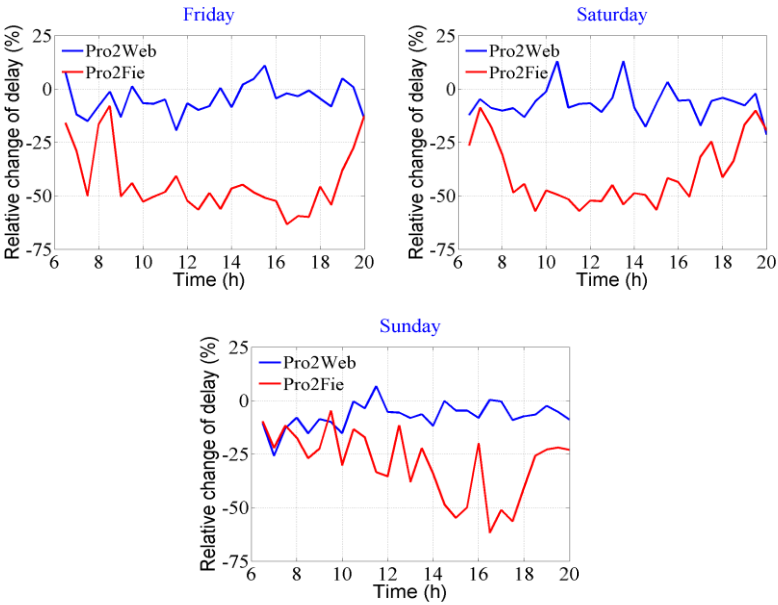


Figure 7-34 Relative change of mean delay in each day of Scenario 2

The relative improvements were time-varying, too. The average and maximal changes in each day is shown in Table 7-3. It was indicated that the average delay reduction by the proposed strategy taking the field plan as the reference was 29.6% at least and 45.0% at most. The average delay reduction by the proposed strategy taking the Webster's model as the reference was 4.5% at least and 7.1% at most. This improvement is comparable to the one obtained in scenario 1.

Table 7-3 Relative change of mean delay over a week of scenario 2

Day	Average percentage change (%)		
	Proposed vs. Field	Proposed vs. Webster's	Webster's vs. Field
Monday	45.0	5.1	41.5
Tuesday to Thursday	37.3	4.8	34.2
Friday	43.7	4.5	40.8
Saturday	39.7	6.5	34.9
Sunday	29.6	7.1	23.5

7.4.4 The test of the raised demand of the second scenario

In order to enhance the credibility of the above conclusion, the demand in SUMO was adjusted for the second scenario by a measurement of the real traffic flow in the whole month of May 2014. The data stem from a few loop detectors, and they were used to scale the demand which goes into SUMO. The scale factor was the ratio of the sum of current traffic flow in SUMO divided by the sum flow detected by the field loops, shown in Table 7-4.

Table 7-4 Scale factor of each hour

Time(h)	Scale factor (real/sumo)				
	Monday	Tuesday to Thursday	Friday	Saturday	Sunday
6	2.86	2.81	2.42	2.98	4.23
7	2.14	1.97	1.88	2.56	3.6
8	2.15	1.92	1.82	1.81	2.57
9	2.9	2.54	2.46	1.53	1.75
10	2.76	2.84	2.73	1.62	1.45
11	3.11	3.31	3.1	1.8	1.69
12	3.41	3.87	3.82	2.35	1.65
13	4.59	2.13	2.53	2.67	2.34
14	5.84	2.5	2.81	2.51	2.13
15	7.52	2.75	3.16	2.66	1.86
16	8.74	3.09	3.96	2.83	1.96
17	9.95	3.5	5.26	2.82	2.07
18	4.85	5.31	6.53	3.55	2.33
19	2.57	5.95	7.49	4.3	2.02
20	2.44	5.79	6.77	3.82	2.52

After the traffic flow had been raised, the traffic signal plans were optimized by the proposed strategy and the Webster’s model every half hour from 6 am to 8 pm. The phase sequences and configuration, as well as, the limited time of phases were set by the restriction of the real traffic signal. All intersections were in the same network by the network partition strategy. The common cycle length of all days were shown in Figure 7-35, where “mo”, “tuth”, “fr”, “sa”, “su” represented Monday, Tuesday to Thursday, Friday, Saturday, and Sunday respectively. It can be seen the field cycle time was 85s, and the optimized cycle was time-dependent in the range of [74, 94]. In most of time, the field cycle time was larger than the cycle optimized by the proposed strategy, especially on Sunday.

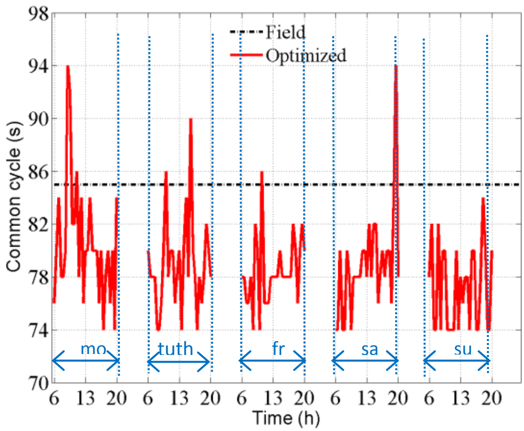


Figure 7-35 Common cycle time with raised traffic flow of scenario 2

The critical intersection that has the first priority order was either “Nr. 47” or “Nr. 5” by the Sorting Model of Priority Order (SMoPO). Then the field and optimized signal plans were simulated, and got the delay time per vehicle of the different plans, which was shown in Figure 7-36. In the figure, the mean delay by the proposed strategy was shown in the red line, by the Webster’s model was in blue line, and by the field signal plans was in black line. The labels including “mo”, “tuth”, “fr”, “sa”, “su” represented Monday, Tuesday to Thursday, Friday, Saturday, and Sunday respectively. It can be seen that the proposed strategy and the Webster’s model outperformed the field plan in all the simulation periods. But the proposed strategy was not always better than the Webster’s model, which confirmed the conclusion in Section 7.3 that the effectiveness of the proposed strategy was related to the traffic demand.

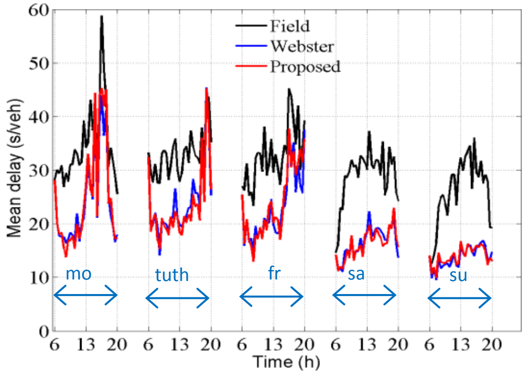
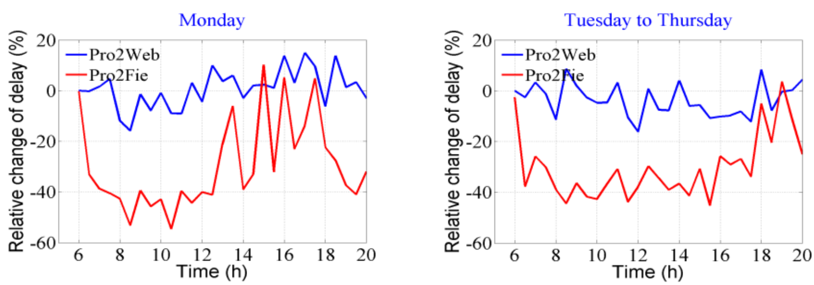


Figure 7-36 Mean delay with raised traffic flow of scenario 2

The relative changes by the proposed strategy compared with the field signal plans (marked as "Pro2Fie") and the plans optimized by the Webster's model (marked as "Pro2Web") was computed by the absolute change divided by the latter delay, shown in Figure 7-37. It can be seen that compared with the field plans, the delay reduction was significant. However, compared with the Webster's model, the proposed strategy performed worse than the Webster's model in about half periods. From optimized cycle (Figure 7-35), the cycle time of successive optimization period fluctuated strongly, that means the traffic demand of successive period fluctuated. But the proposed strategy used the traffic demand of the previous period to optimize the current traffic signal. In this way, the optimized control plan would be not fit for. For instance, at 9:30 of Monday, the proposed strategy underperformed the Webster model by about 7.8%, the optimized cycle of that successive periods changed from 80s to 94s. For this drawback of the proposed strategy, the forecast model of traffic demand should be developed in future.



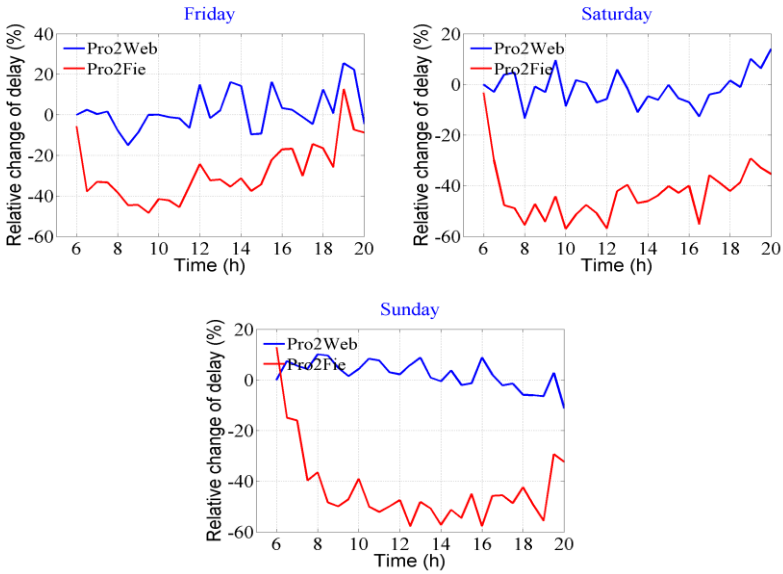


Figure 7-37 Relative change of mean delay with raised traffic flow of scenario 2

7.5 Summary

In this chapter, the performance of the proposed strategies and models were evaluated by the simulation tool, SUMO. Firstly, the speeds of the priority order model SMoPO, the network partition strategy, and the network signal coordination strategy were tested to verify their feasibility to be real-time capable. The trial network is n-by-n grid net from the scale of 3-by-3 to 60-by-60. It was known that that the computation time of priority order model increased in the third-degree polynomial and the time of network partition strategy and coordination strategy increased linearly with the network scale. The coefficients of determination (R-square) were more than 98%. The computation time for the largest net (the net has 3600 intersections) was 94.86s of priority order model, 1.1s of partition strategy and 16s of signal coordination strategy.

Secondly, the 8-by-8 grid net with the same link length was used to evaluate the effectiveness, application scope and robustness of the proposed strategies. In terms of effectiveness, the comparison method was the Webster's model, and the measures of effectiveness were mean delay time, mean fuel consumption and mean PMx emissions. In terms of the application scope, the traffic demands were divided into three levels. The vehicles per O-D pair per hour in the range of [200, 400], (400, 800) and [800, 1000] were defined as low, medium and high traffic demand respectively. In terms of robustness, fifty O-D matrixes in each demand level were created randomly whose elements were drawn from a uniform distribution. The experiments' results showed that in low traffic demand, the delay by the proposed strategy compared with the Webster's model was increased by about 2%, but the fuel consumption and PMx emissions were decreased by about 5% and 10%. In medium traffic demand, the delay was decreased 2% at least and 18% at most, and the fuel consumption and PMx emissions were decreased by about 3% and 4%. In high traffic demand, the delay and fuel consumption were increased and the PMx emissions were decreased a little. It was concluded that the proposed strategy was effective in low and medium traffic demand level.

Besides that, the performance of the proposed strategy was evaluated in the 8-by-8 grid with varied link lengths. The traffic demands were created as before. The results indicated that the delay, fuel consumption, and PMx emissions by the proposed strategy were lower than the Webster's model in medium and high traffic demands. However, the proposed strategy performed worse than the Webster's model in the low traffic demand.

Thirdly, the feasibility and effectiveness of the proposed strategy were tested in two real networks in Braunschweig City. Both scenarios indicated the strategy was effective. The delay of the first scenario was decreased by 6% compared with the Webster's model, by 30% compared with the original plan. The delay of the second scenario was decreased by 5% compared with the Webster's model, by 40% compared with the field plan. The reason of the bad performance of the field signal plans was the traffic demand in the simulation was lower than the real traffic demand. In scenario two, an additional test was performed, where the traffic demand has been adapted to real measurements in the field. Still, the proposed strategy showed improvements over the plan used in the field, while its performance was not superior to plans created by the Webster's model all the time.

Chapter 8
Conclusions

8.1 Summary

Nowadays, most of the cities' traffic lights are still controlled in time of day (TOD) mode, although some adaptive traffic control systems have been operated successfully, and shown effectiveness in some cities, such as Beijing, London, Sao Paolo and Southampton etc. (Dey et al., 2002). The reason including both subjective and objective was discussed in Section 1.1. With the development of information acquisition, data mining and computer power, as well as, greater concentration on environmental issues, the problem of intelligent traffic control becomes worth studying further.

Some adaptive control systems are developed and operated in some cities, and some systems, models, and algorithms are available in the literature. They were introduced in the second chapter. In this thesis, a novel method was proposed.

It first computes the so-called priority order of the intersections in the network by a model named Sorting Model of Priority Order (SMoPO). The model takes into account the intersection's location in the network and the saturation degree of links. A traffic signal optimization tool, TRANSYT, was used to demonstrate the effects of the sorting model since it has a setting of optimization order. In two test cases, SMoPO turned out to compute an optimal order that brought better performance.

Based on the intersections' priority orders, a network partition strategy and a network signal coordination strategy were developed, which were introduced in Chapter 4 and 5. They are based on the greedy search algorithm. Traditionally, a network was partitioned into subnets often by choosing some boundaries, such as rivers, administrative boundaries, major arterials or freeways, etc. However, the traffic status varies with the time and the traffic signal need be optimized real-time, so the network partition should be dynamic with the change of traffic states. Some dynamic network partition approaches were proposed, which were depicted in section 4.1. However, these researches only concerned network partition without the subsequent signal optimization. It is thought in this thesis the network partition and the network signal coordination is an integral with the consistent objective. Therefore, the two characters of the two strategies are dynamic and associated.

To assess the dynamic feature, amounts of speed tests were done in Section 7.2. The trial network of simulations was n-by-n grid network from the network scale of 3-by-3 to 60-by-60, which interfaced with an open-source simulation tool SUMO. The simulations' results showed that the computation time of priority order sorting model increased in the third polynomial, and the time of the network partition strategy and the network coordination strategy increased in linear with the network scale. The computation time for the trail network with 3600 intersections (a network scale larger than Berlin, Germany) was 94.86s of the priority order, 1.1s of the partition strategy and 16s of the signal coordination strategy, about 112s in total. The speed can be faster by enhancing computer's CPU.

As the two macro control strategies were presented, the calculation methods of micro-timing parameters including common cycle time, effective green time and offset were discussed in Chapter 6. An offset estimation method based on the cyclic flow and cyclic delay was proposed. Now, by this series of strategies the signal timing plan of each intersection can be computed in real-time. The effectiveness of the strategies was tested in an eight-by-eight grid network and two real networks in Braunschweig, Germany, which was described in Section 7.3 and 7.4.

The grid network was used to verify the effectiveness, application scope and robustness of the proposed strategies. The comparison method was the Webster's model, and the measures of effectiveness were mean delay time, mean fuel consumption and mean PMx emissions.

The experiments' results showed that, the proposed strategy outperformed the Webster's model in fuel and PMx by about 5% and 10% but underperformed in delay by about 2%, when traffic demand was low defined as vehicles per O-D pair per hour were in the range of [200, 400]. It indicated the proposed strategy was effective when taking the fuel consumption and PMx emissions as MOE. One of the reasons was that the signal coordination decreased stop times, and the fuel consumption and PMx emissions were the function of the travel time and stops etc. In low demand level, the effect on delay time from the signal coordination was not obvious since traffic flow was too small, but the effect on stops was still strong.

The proposed strategy outperformed in delay time, fuel consumption and PMx emissions by about 10%, 3% and 4%, when the traffic demand was medium defined as vehicles per O-D pair per hour were in the range of (400, 800). Namely, it was effective in medium traffic demand network in all three MOE.

The proposed strategy outperformed in PMx emissions, but underperformed in delay time and fuel consumption when the traffic demand was high defined as vehicles per O-D pair per hour were in the range of [800, 1000]. Because the demand has exceeded the road capacity so that the traffic signal has no capability to improve the traffic status. Moreover, due to microscopic models' calibration is not very exact under congested conditions. All the cases showed the high robustness of obeying the conclusions. The case studies for varied link length nets indicated the strategy was effective too.

In the real network tests, the signal plans were optimized every half hour. The delay in two scenarios was decreased by about 6% compared with the Webster's model, by about 30% compared with the original plans and field plans. So it can be said the proposed strategy was successful.

8.2 Outlook

To improve the proposed optimization strategies in this thesis, additional work is required to be done in the future. Firstly, although the experiments in Chapter 7 indicated that the optimization strategy worked well, more simulation experiments are still necessary to be done in the future, and analyze the bad optimization cases that has been observed. This will help to find the defects of this strategy and modify it. The simulations should contain field scenarios and hypothetical scenarios. For the field scenario, the available field data including traffic demands and signal plans are the issues that need to be solved in the future. For the hypothetic scenario, it is better to build some default networks and program an input data generator. So that the case can be analyzed automatically, and long-term experimental analysis could be available, and much more detailed statistics could be produced. The field implementation of the schemes optimized by proposed by the strategy might be an achievable thing to calibrate the simulation work. Besides, visualization of the effect of the optimization strategy is an interesting work for the next step. And the degree of interference to the performance by the traffic demand fluctuation and how to prevent are interesting topics too. An optimization package can be developed based on this strategy and interfaced with simulation tool SUMO (or any other microscopic simulation software).

As Sir Isaac Newton said that “Truth is ever to be found in simplicity, and not in the multiplicity and confusion of things”. This idea was held during the research. This research is meaningful and valuable, and there is still much work needs to do in the future.

List of Figures

List of Tables

List of Abbreviations

A

ACA: Ant Colony algorithm

ACS-Lite: The Adaptive Control Software Lite

ACTRA: Advanced Control and Traffic Responsive Algorithm

AIM: Anwendungsplattform Intelligente Mobilität

AP: Arithmetic Progression

ATSAC: Automated Traffic Surveillance and Control System

C

CBD: the Central Business District

CEM: Cross Entropy Method

CI: Coupling Index

CTM: Cell Transmission Model

CYOP: Cycle Time Optimiser

F

FHA: Federal Highway Administration

FHWA: Federal Highway Administration

G

GA: Genetic algorithm

H

HCA: Hill Climbing Algorithm

HCM: Highway Capacity Manual

I

IOA: Optimization Assignment

IRS: ITS Roadside Stations

ITACA: Intelligent Traffic Adaptive Control Area

M

MC: Mutually Consistent

MILP: Mixed-integer Linear Programming

MME: Mean Modulus of Error

MOEs: Measures of Effectiveness

N

NLP: Non-Linear Program

O

O-D: Origin-Destination

OPAC: The Optimization Policies for Adaptive Control

P

PI: Performance Index

PRODYN: Programming Dynamic

PSOA: Particle Swam Optimization Algorithm

R

RHODES: The Real-time Hierarchical Optimized Distributed Effective System

RO: Robust Optimization

RONDO: Rolling horizon based Dynamic Optimization of signal control

RT-TRACS: Real-Time Traffic Adaptive Control System

S

SA: Simulated Annealing

SCATS: The Sydney Coordinated Adaptive Traffic System

SCOOT: The Split, Cycle, and Offset Optimization Technique

SMoPO: Sorting Model of Priority Order

SoA: Strength of Attraction
SPSA: Simultaneous Perturbation Stochastic Approximation
SUMO: Simulation of Urban MObility

T

TOD: Time Of Day
TRANSYT: TRAffic Network Study Tool
TRRL: Transport and Road Research Laboratory
TSIS/CORSIM: The Traffic Software Integrated System - Corridor Simulation

U

UE: User Equilibrium
UTCS: the Urban Traffic Control System
UTOPIA/SPOT: Urban Traffic Optimisation by Integrated Automation / System for Priority and Optimisation of Traffic

V

VFC-OPAC: Virtual-Fixed-Cycle Optimization Policies for Adaptive Control
V2I: Vehicle-to-Infrastructure

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